

# Electricity

Efficient End-Use and  
New Generation Technologies,  
and Their Planning Implications

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# The Challenge of Choices: Technology Options for the Swedish Electricity Sector

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## Abstract

In this chapter we illustrate alternative future developments of the Swedish electricity sector, based on the new electricity supply and end-use technologies discussed in the other chapters in this volume. We develop integrated electricity supply/demand scenarios in which all electricity services associated with a 1.9% annual growth in gross domestic product are delivered, and in which all nuclear power plants are phased out by 2010, as decided by the Swedish Parliament. The scenarios vary in the degree of end-use efficiency assumed and in the reliance on fossil-fuel supply technologies. See the conclusions section for a comparison of the resulting costs and carbon dioxide emissions.

## 1 Introduction

The power production industry in Sweden is facing a major change. Following a public referendum in 1980 and several subsequent Parliamentary decisions, nuclear power, which now provides about one-half of the country's electric energy and one-third of its generating capacity, will be phased out by the year 2010. Other related national objectives include continued economic growth, improved environmental quality, reduced oil consumption, and increased use of sustainable, preferably renewable and domestic energy sources.

Environmental goals place strict demands on the electricity system in Sweden, some of which are potentially conflicting in nature. Hydroelectric

power now provides the other half of Sweden's electricity. After some minor expansion, the construction of additional hydropower capacity will be forbidden by law. Fossil fuels are not an easy alternative in light of a Spring 1988 decision by Parliament to set general guidelines restricting carbon dioxide emissions to their present level, and encouraging their overall reduction. Meanwhile, official forecasts of electricity demand indicate continued growth from today's value of 130 TWh/year to 145 TWh/year in 2010, including losses (1), with a broad range of uncertainty.<sup>1</sup> This forecast implies a 0.5%/year demand growth rate, much reduced from the 3.9% annual rate in the 1970-82 period and the 5.2%/year rate between 1982 and 1987.

All the above-mentioned factors will have great implications for the strategy of utilities in Sweden as they plan for the future. The global importance of the CO<sub>2</sub> problem could lead to a much larger-scale planning challenge involving many countries. If nations follow the recommendations of the 1988 Toronto conference – to reduce CO<sub>2</sub> emissions by 20% by the year 2005 – key strategies will address the end-use efficiency of energy as well as the choice of primary energy sources and conversion technologies (2).

Around the world, development of technologies for electricity production and end-use efficiency is proceeding, and consumer-oriented efficiency improvement programs are emerging. Most of the existing experience with demand-side management lies with the North American utilities. However, in Sweden, Vattenfall (the Swedish State Power Board) is conducting the "Uppdrag 2000" project to help demonstrate efficient end-use technologies and identify the country's efficiency potential by working directly with power and heat customers, suppliers, and equipment manufacturers.

## 1.1 Conceptual Approach

One way to gain perspective on the current situation is to construct scenarios that shed some light on the various possibilities and their implications. This chapter presents scenarios that focus especially on the technological options. Our objective is to examine the technologies and strategies that could be chosen to meet the multiple objectives i.e., with respect to the nuclear phase-out, keeping CO<sub>2</sub> emissions constant, and maintaining economic growth. Our analysis makes use of the assessments provided in the other chapters of this

book and draws as well on other state-of-the-art studies of electricity-efficient end-use and generation technologies.

We begin with the simple observation that electricity *per se* is not of interest, but rather that the demand for electricity is a reflection of the demand for the *services* it can provide: hot showers, cold herring, clean clothes, illumination, motive power, maintenance of a comfortable indoor climate, data storage/retrieval and so on. This perspective has led us to adopt end-use oriented methods in the preparation of our scenarios. Framing the analysis in terms of energy services helps to identify options and constraints that affect the electricity demand-supply balance, while delivering all of the energy services demanded by electricity users in a growing economy. This was in fact the perspective of Thomas Edison in starting the first electric utility. His ambition was to sell *illumination*, rather than electricity, realizing that as the efficiency of lamps inevitably increased that his profits would also increase.

The boundary conditions of our study include all present (1987) electricity services from the direct uses of electricity in Sweden, and, because of the linkages in the supply sector, the energy services from district heating and from the heat produced in industrial cogeneration. Our analysis, then, does not include the energy services derived from fuel presently used in transportation, space heating, and industry, except that consumed in cogeneration. Today's interruptible power (about 10 TWh/year, consumed in large electric boilers used in the district heating systems and industry), is also excluded from the analysis.

The scenarios developed below are all based on the same growth in these services, resulting from projections of 1.9% real growth in gross national product over the 1987-2010 period. This growth rate reflects average growth, which is the same as that used in the long-term economic forecasts made by the Swedish Ministry of Finance (3).

Our approach employs electricity demand models and techniques that are used in the planning work at Vattenfall, with the exceptions noted below. We make use of the same future activity levels in all sectors and changes in lifestyle as those used in a recent Vattenfall demand scenario study.

The demand-side scenarios are constructed in the following way:

- *Reference Scenario.* This is one of several scenarios developed by Vattenfall for use as input into the planning of future power production needs (4). We chose a scenario close to the middle of the current official forecast interval for 2010 (5). This scenario is based on past Swedish experience of the market's behavior, and assumes no policy measures (e.g., incentives, standards, information) beyond those already existing and an anticipated 50% real electricity price increase. Thus, adoption of efficient end-use technologies is based on the assumption that the decision makers – e.g., electricity consumers, retailers, consultants, and utilities – will act on their

<sup>1</sup> This is the Vattenfall extension of the current forecast interval for 1997 to the year 2010. The 145-TWh demand level represents the center of a 120-170 TWh/year range projected for the year 2010. The corresponding range of average growth rates is -0.4%/year to 1.2%/year.

own accord and invest when motivated to do so by their individual perceptions of payback time, discount rates, and non-economic factors.

To prepare for developing the remaining scenarios, we employ a computational aid that we call the "Frozen-Efficiency baseline". The demand level corresponding to frozen efficiency is a projection of demand as it would develop given the increase in long-term economic activity, and associated structural change within the anticipated GDP growth, but no improvement in efficiencies compared to the base-year levels. The Frozen-Efficiency baseline thus represents the "electric energy service" level in the target year, based on efficiencies in 1987. With the following three scenarios, we then explore potential impacts of existing and emerging technological opportunities discussed in this book. The efficiency levels of electricity-efficient technologies are assumed to become average efficiency levels in the stock at the rate of capital turnover and expansion. Fuel switching, from electricity to oil and natural gas, is also incorporated. In contrast to the Reference Scenario, these scenarios utilize efficient end-use technologies that are cost-effective from a societal perspective (6% real discount rate), rather than from a private perspective.

- *Efficiency Scenario.* This scenario is based on high penetration of the most efficient end-use technologies commercially available<sup>2</sup> and cost-effective in comparison with new electricity supply.
- *High-Efficiency Scenario.* This scenario is based on the previous scenario plus adoption of selected end-use technologies for lighting, motors, and several household appliances, in advanced stages of development or already developed but not yet commercialized.
- *Advanced-Technology Scenario.* This scenario is intended to show the effect of adopting additional technology measures and strategies, still at the research and development stage, that can not at this time be judged to be cost-effective.

It must be stressed that scenarios are not forecasts. The last three scenarios represent in no way what *will* happen, but rather what *could* happen if information, education and training, regulations, and incentives are orchestrated to steer the decisions of the many electricity users as well as investors and designers in this direction (see Section 6).

On the supply side, we determine the amount of new generation necessary to meet the difference between the demand levels resulting from each scenario and the existing non-nuclear capacity. We adhere to Sweden's standards of electrical system reliability, insuring that it remains at or above today's criteria for reliable operation. The power generation technologies are assumed to be

among the most efficient available and meet Sweden's environmental guidelines planned for 1995. Various options to provide the required electricity are then organized into three generation scenarios:

- *Economic Dispatch.* The first scenario is based on the traditional notion of economic dispatch – new power plants are constructed and utilized in order of increasing costs per kilowatt-hour supplied, including all costs for complying with present environmental regulations.
- *Natural Gas/Biomass.* The second scenario includes currently unutilized forest residue resources and some wind, and then proceeds with economic dispatch, excluding coal-based technologies.
- *Environmental Dispatch.* The final generation scenario specifies new power plants in order of increasing net carbon emissions per unit of electricity supplied. Biomass fuels from energy plantations are utilized in this scenario.

To facilitate comparisons between investments in conservation and in new generating capacity, all economics evaluations of the scenarios are made using a 6% real discount rate and do not incorporate the effects of direct energy taxes. For efficiency improvements, we use the annualized investment cost divided by annual savings as our cost-effectiveness indicator. For traditional power plants and wind, we adopt cost estimates used by the Swedish power industry. For new technologies, cost estimates (which by definition have higher uncertainty due to lack of experience) are taken from other chapters in this book. We use the 1987 world prices for oil and coal. The price of natural gas is selected to equalize the busbar costs from gas- and coal-fired condensing power stations based on the assumption that future gas prices will be negotiated this way. The cost estimate for domestic biomass is also based on a 6% real discount rate, and is therefore below the present market price. Real energy prices are assumed to be constant during the 1987-2010 planning period. The basic assumptions are presented in Box 1.

Finally, by integrating our analyses of the demand- and supply-side options, we describe a range of choices and their key economic and environmental implications.

## 2 Electricity Demand Scenarios

### 2.1 Methodology

To develop scenarios of future electricity demand, we employ four overview electricity demand models used at Vattenfall: one each for residential

<sup>2</sup> By "commercially available" we mean technologies that are available in today's marketplace.

**Box 1. Key economic, demographic, and structural assumptions in the scenarios.** (All growth statistics are for the 1987-2010 period)

*General*

- Population growth (million): from 8.41 to 8.60 (0.1%/y).
- Gross domestic product: 1.9% real annual growth (index: 100 → 154).
- Private consumption: 1.5% real annual growth (index: 100 → 141).
- Public consumption: 0.9% real annual growth (index: 100 → 123).
- Nuclear power phase-out period: 1995-2010.
- Energy prices: real world market oil prices, \$20/barrel crude (equals \$26 heating oil) [the Reference Scenario uses \$30/barrel crude in 2010]. Fuel prices for power generation (fuel basis, lower heating value): Coal, 0.60 cents/kWh<sub>th</sub>; natural gas, 1.10 cents/kWh<sub>th</sub>; biomass, 1.25 cents/kWh<sub>th</sub>. All energy prices reflect costs to Sweden, net of direct taxes. 1 US\$= 6.3865 Swedish kronor.

*Household Appliances*

- The number of households (million): single-family – grows from 1.77 to 1.88; multi-family – grows from 1.95 to 2.24.
- Persons/household: decline from 2.82 to 2.67 (single-family) and from 1.75 to 1.60 (multi-family).
- Degree of appliance saturations: Trends in saturation reflect lifestyle changes that include the increased consumption of white goods. (See footnote 3).

*Service Sector*

- Floor area (million m<sup>2</sup>): 148 existing in 1987, 23 additions, 5 demolitions.
- 1987 end-use shares and annual increase in electricity service to 2010: lighting (31%, 2.3%); motors, pumps, fans, etc. (37%, 3.1%); food preparation and refrigeration (17%, 1.6%); office electronics (14%, 4.5%); other (1.5%, 4.5%).

*Industry*

- Structure: overall output increases by 2.6%/year (value added). The output of mining and textiles declines, respectively, by 1.5% and 1.0% annually. The greatest growth is in the engineering sector – 3.6% annually; chemicals 2.2%/year. Steel industry output 0.8%/year; The largest electricity use is in paper and pulp where output grows at 1.6% annually.

*Electric Space Heating and Domestic Hot Water*

- Electric heating equipment, GWh and million m<sup>2</sup> in 1987:  
[Electric resistance; electric boilers; heat pumps; multi-fuel furnaces]
- Single-family homes – 8,700 (69.0); 4,300 (31.0); 390 (5.9); 5,800 (76.6).
- Multi-family homes – 900 (5.1); 500 (2.5); 500 (3.6); 2,600 (19.5).
- Service sector – 1,600 (8.0); 720 (4.4); 100 (1.7); 860 (15.7).
- Multi-fuel heating equipment in single-family homes: net conversions 13.5 million m<sup>2</sup>, new homes 20.5 million m<sup>2</sup>, demolitions 9 million m<sup>2</sup> (Reference scenario only.)

appliances, services, industry, and space plus water heating. These models are end-use oriented and are essentially based on the notion that total electricity demand is the product of specific use (efficiency) and activity level (structure and utilization), summed over all activities in society. The models incorporate many sources of data on the structure and intensity of electricity demand in Sweden. Total electricity demand is obtained by adding the results from the four models. When forecasting, Vattenfall uses these models plus more detailed material and supplementary models. Where possible, the results of interviews with energy users, large buyers, and firms supplying energy-using equipment are also incorporated. The size of Sweden makes it possible to incorporate customer-specific data, especially within the industrial sector.

The models vary, however, in their suitability for estimating the impacts of changes in end-use efficiency. The residential appliance model is the most well-suited for this purpose because it explicitly accounts for the efficiency of many different appliance end-uses and degree of saturation, lifestyle factors affecting them, and for their lifetimes in the stock. Because of lack of data, the service sector model is the least developed; it provides only minimal end-use breakdowns without explicitly separating efficiency and structural-change factors.

This section will briefly describe the concept and structure of each model. Section 2.2 will then describe the scenarios that we have developed using the models.

### 2.1.1 Residential sector appliance model

In this model, appliance saturation, stock turnover, and efficiency are specified for 35 residential end-uses, including “cottage industry”, well pumps on farms, and even “weekend apartments” rarely occupied. Trends in private consumption, home area, persons per household, mix of single- and multi-family homes, utilization, saturation, and technical improvements are all specified in the model. In addition, small adjustments are made to account for a slight deterioration of efficiency as individual appliances age and for product-change factors such as the anticipated increased use of microwave ovens.<sup>3</sup>

<sup>3</sup> Structural change plays a large role in the development of household appliance electricity use between 1987 and 2010. For example, in single-family homes, the saturation of combination refrigerator/freezers increases from 9% to 40%; the saturation of single electric stoves decreases from 84% to 30% with a shift to microwave/electric stove combinations – increasing from 14% to 70%; the use of electric clothes dryers grows from 18% to 85%; and 45% of the homes are expected to have two combination refrigerator/freezers in the year 2010 versus only 6% of the homes in 1987. The model also accounts for growth in electricity services such as increasing TV size and viewing time, refrigerator volumes, etc.

For some of the major appliances (refrigerators, freezers, and combination units), a separate stock/vintage model is used to trace each year's cohort of new appliances through their lifetime in the stock. A logit function reflects that some appliances remain in use for much longer than the average lifetime.

Surveys conducted by National Bureau of Statistics, and interviews with large buyers (e.g., housing management companies) are used to incorporate consumer preferences into the estimates future appliance type, saturation, and efficiency. The most attention is given to refrigeration, especially in multi-family buildings where they represent 40% of non-heating electricity use. Price effects are not accounted for explicitly and are assumed to play a much smaller role in determining efficiency than does technological change.

### 2.1.2 Service sector model

In this model, electricity demand in 17 sectors is separated into lighting, motors, food preparation and refrigeration, general office electronics, and "other" end-uses.<sup>4</sup> Future demand is estimated based on official projections of changes in employment, floor area per employee, number of firms, and so on (6). Sub-calculations are made for floor-area-independent demand (e.g., trains). The existing end-use and sub-sector data are so limited that no clearly separable efficiency effects are included in the forecasts made with this model. Instead, trended projections based on historic electricity-per-employee statistics are the determining factors. The growth rates prior to 1982 – when the promotion of electric heating was escalated in Sweden – are used by Vattenfall to estimate non-heating electricity trends for the future. Price effects are not formally included in the model.

### 2.1.3 Industrial sector model

Industrial electricity demand is modeled using a series of linked matrices, each containing parameters relevant to electricity demand. The matrices include fuel share, efficiency improvement, and production. For each matrix, different rate-of-change assumptions are made for four time periods between 1987 and 2010. The model distinguishes among ten sectors plus "small industry", defined as firms with five or fewer employees. End-uses include transport, lighting, processes (four sub categories), and a space heating and "other" category for offices. Demand for each end-use is assumed to grow in direct proportion to

production and is then modified by an efficiency parameter. Production is measured in monetary terms, but for the paper and pulp and steel industries production is also measured in physical units. Price effects are not explicitly accounted for in the model. (When used for forecasting, high future prices are assumed to result in the elimination of some electricity-intensive processes, e.g., certain electric arc furnaces, and sometimes to precipitate the closure of entire firms.)

### 2.1.4 Space heating and domestic hot water model

Space and water heating in all sectors, except industry, are incorporated into one model. Single-family homes, multi-family homes, vacation homes, the service sector, and large heat pumps are treated separately. Virtually no detail is included on water-heating for domestic purposes, an end-use that represents roughly 5 TWh<sub>e</sub> per year in single-family homes. For space heating, an attempt is made to separate the effects of projected stock additions, demolitions, efficiency improvements, and price-induced conversions to and from electricity. In addition, about 50% of all efficiency improvements in the appliance model are counted as increased electric heating in homes that have electric heating, because the reduced waste heat from these appliances will increase the need for electric space heating during part of the year.

There is a large quantity of "hidden heating" in Sweden, i.e. electric heating used by customers that are counted as fuel-heating customers in the national statistics but in fact use electric heaters as well as (or instead of) fuel. Vattenfall estimates that single-family homes had at least 2.1 TWh of hidden heating in 1986<sup>5</sup> and multi-family homes 1 TWh.<sup>6</sup> This special type of heating is included in the heating model. Electric space heating in industry is included as an end-use in the industrial model, rather than in the space heating model.

## 2.2 The Demand Scenarios

The scenarios we develop in the following pages are intended to illustrate a range of choices. The demand scenarios differ in the assumptions made about end-use efficiency and the choice of energy carrier for heating, and in the

<sup>5</sup> The PREDECO model and data bases (Lars-Göran Carlsson, personal communication, October 10, 1988) gives a somewhat higher figure for single-family homes, 2.4 TWh for 1986. Note also that electricity consumption in vacation homes has risen from an average of 2,718 kWh/year in 1972 to 4,281 kWh/year in 1986. These homes are not subject to the national thermal construction standards.

<sup>6</sup> Personal communication, Gunnar Larsson, Vattenfall, October 31, 1988.

<sup>4</sup> This sector includes a wide variety of customers and they are grouped in the model into two categories: floor-area dependent (e.g., retail stores, wholesale stores, banks, athletic facilities, insurance, and defense) and floor-area independent (e.g., street lighting, trains, agriculture, and construction companies).



conservation investment criteria used, as explained in Section 1.1. All other economic growth, demographic, and structural factors are held at values based on long-term studies from the Ministry of Finance (see Box 1). The choice of the year 2010 as an “end-point” is made because considerable attention is focused on this date in other energy studies and discussions in Sweden. Of course, the technology changes described here are ones that would occur gradually and the exact year of full implementation would be a function of many factors.

In the following scenarios, we allow ample time for capital turnover. Net additions to the buildings stock are taken directly from those assumed in the Vattenfall model. The 23-year time horizon of each scenario (1987-2010) is longer than the lifetime of household appliances and is well within the time necessary to formulate and deploy programs, incentives, etc., designed to stimulate adoption of more efficient technologies at the time when replacement decisions are being made. This time period is also longer than the lifetime for many technologies in the industrial sector, especially given that equipment is often replaced because there is an economic gain from doing so, rather than because it is “worn out”. Aside from these considerations of capital turnover, the exact shape of the path from 1987 to 2010 is not analyzed.

All calculations and assumptions are shown in (7), a detailed companion document to this chapter. Brief supporting information and sources are given in the footnotes. The assumptions are based on chapters in this book and other published sources.

### 2.2.1 Frozen-Efficiency electricity demand

The level of electricity *services* required in 2010 can be thought of as today’s activity level plus all growth in activity that would occur if the economy expanded as shown in Box 1 and end-use electricity efficiency remained at its 1987 level – e.g., a 10% increase in steel production and no change in electricity use per ton of steel yields a 10% increase in the electricity services provided and a 10% increase in the electricity required. New technologies are thus assumed to have the same electricity efficiency as the present average.<sup>7</sup>

<sup>7</sup> Determining the Frozen-Efficiency baselines for space heating and for the service sector is not as straight-forward as for other sectors. In developing the heating baseline, we assume that there are no efficiency improvements beyond 1987, conversions to electricity occur as shown in the Reference Scenario, new homes are constructed at today’s average use per home, and internal heat gains increase according to the Frozen-Efficiency baseline for household appliances. The baseline for the service sector is an extrapolation of the 1970–1987 growth trend. Although an attempt has been made to remove electric heating from the historic data

This “Frozen-Efficiency” baseline is included as an analytical tool only, in order to be able to isolate the impact of efficiency in the scenarios from that of other factors embedded in the models.

The resulting level of electricity services (measured for the remainder of the chapter in units of TWh equivalent, TWh<sub>eq</sub>) forms a basis from which to measure prospective efficiency improvements, without double-counting those embedded in any previous forecast or scenario. Box 2 contains the efficiency assumptions used in each of the following scenarios.

### 2.2.2 Reference Scenario

The Reference Scenario estimates electricity demand in 2010, assuming market-driven conservation behavior in an environment with real electricity prices 50% higher than today’s.<sup>8</sup> Conservation effects are included, based on individuals’ investment perspectives. Fuel-switching in homes is based on an economic comparison of electric resistance heating only, multi-fuel systems, or oil-only systems. Given time-of-use rate structures, customers are assumed to switch heating systems if there is at least a \$85/year net benefit from doing so.<sup>9</sup> This is intended to reflect historic consumer behavior. The scenario assumes the implementation of 90% of those changes fulfilling this criterion. An average tariff (*mellantariff*) is used for those with only electric resistance systems. The scenario results in a net 3 TWh of conversions to electricity, mostly as a result of rate structures that favor the use of electricity for summertime water heating. An additional 0.6 TWh increase in space heating demand results from the net demolition/construction of buildings.

New buildings in the service sector are assumed to use 140 kWh/m<sup>2</sup>-year (excluding electric space heating), due to the increased number of electric end-uses. As a result of retrofits in existing buildings, the stock average remains at the present level of ~100 kWh/m<sup>2</sup>-y in 2010. Developments in the industrial sector are quite varied. Efficiency as well as production volume decline in some sectors and increase in others. The average efficiency of household appliances in 2010 is expected to be near today’s best, due to technological change that is only partly driven by design changes intended to reduce electricity use.

series upon which this estimate is based, the absence of high-quality statistics leaves open the possibility that heating growth in the 1980s has biased the extrapolation.

<sup>8</sup> This is one of six scenarios (Scenario “F”) developed at Vattenfall in the Spring of 1988 (22).

<sup>9</sup> Defined as the difference between the value of annual energy cost savings and the levelized capital cost of the conversion. Typical wintertime furnace efficiencies of approximately 80% are assumed.

**Box 2. Efficiency assumptions in the Scenarios.\*** (Except where noted otherwise, the numbers shown refer to the percent of base-year intensity)

#### *Appliances<sup>a</sup>*

("Reference"), "Efficiency", "High-Efficiency", and "Advanced-Technology" Scenarios

Food storage (69), 49, 24, 24  
Food preparation (86), 85, 69, 69  
Lighting (61), 60, 59, 59<sup>b</sup>  
Dish and clothes washing/drying (56), 55, 19, 19  
Miscellaneous appliances (89), 89, 76, 76

#### *Services*

Lighting (55), 36, 30, 30<sup>b</sup>  
Motors, pumps, fans, compressors (70), 65, 60, 60<sup>c</sup>  
Refrigeration and food preparation: 60 in all cases<sup>d</sup>  
Office electronics (65), 32, 20, 20<sup>e</sup>  
New buildings 140 kWh/m<sup>2</sup>, 50 kWh/m<sup>2</sup> in all other cases (excludes space heating)<sup>f</sup>

#### *Industry<sup>g</sup>*

Lighting: (71), 45, 40, 40<sup>b</sup>  
Motors, pumps, fans, compressors (85), 70, 60, 50<sup>c</sup>  
Mechanical pulping: (included in total motors), 90, 80, 70<sup>c</sup>  
Process heating: (60)\*\*, 80, 80, 80<sup>h</sup>  
Electrolysis: (75)\*\*, 85, 85, 85<sup>i</sup>  
Steel scrap-melting: (included in process heat), 80, 25, 25<sup>j</sup>  
Conversions from electricity to natural gas (TWh<sub>e</sub>): (0), 2.1, 3.6, 3.6<sup>h</sup>

#### *Space and water heating*

Multi-fuel furnaces – conversion to oil (CO) or earth-source heat pumps (HP)  
[COP 2.7 Efficiency Scenario, 3.3 High-Efficiency and Advanced-Technology]:  
(0% (CO) and 0% (HP)), 72% and 18% penetration in all other cases<sup>k</sup>  
Existing heat pumps estimated to have COPs ~ 2.3 and are replaced (over 23 years) with the efficient models described in the previous note.  
Electric boilers – earth-source heat pumps in homes with electric boilers:  
(0%), 90% penetration in all other cases<sup>l</sup>  
Large heat pumps: (60% conversion), 80%, 80%, 100%<sup>m</sup>  
Envelope retrofits in homes with direct electric resistance heating (penetration):  
(not indicated), 50% roof retrofits, 20% wall retrofits in all other cases<sup>n</sup>  
New homes: (8,000 kWh/year for space and water heating), 2,500 kWh/year space heat and 2,500 kWh/year water heat in all other cases<sup>o</sup>

\*Notes to the Box are located before the references section, page 940.

\*\*Includes price-induced plant closures (Reference Scenario only).

The Reference Scenario values are enclosed in parentheses to distinguish them from those for the other scenarios. The Reference Scenario numbers are *implied* by the Frozen Efficiency results, i.e., they were not used to derive the scenario.

### 2.2.3 Efficiency Scenario

In this scenario, we retain all of the structural factors from the Reference Scenario and explore the effect of high penetration of the best commercially available and cost-effective efficiency technologies described below and in greater detail in Box 2.

#### *Household appliances*

We assume that the efficiencies of presently best-available appliances become average in the stock.

#### *Service sector*

In the service sector, we estimate the potential efficiency improvements from new lighting technologies; adjustable-speed drives for motors, pumps, fans, compressors (and more efficient motors and systems design); and retrofit of food refrigeration and preparation equipment in existing buildings, and from high-efficiency office electronics. Measured results from 206 U.S. buildings show median electricity savings of 19% from retrofits, roughly 90% of which had payback times of five years or less (23).<sup>10</sup> New buildings are assumed to be constructed with electricity intensities comparable to the values described by Abel in this volume (24) and from the measured performance for several hundred of the best buildings known (25, 26).

#### *Industry*

In industry, we estimate the increased energy productivity opportunities from improved lighting, adjustable-speed drives and more efficient motors, used in well-designed systems moving gases or liquids, process-heat conservation measures and fuel switching (2.1 TWh<sub>e</sub>), and efficiency improvements in "office" equipment.

<sup>10</sup> Including fuel and electricity, this study contains 311 buildings (schools, small offices, hospitals, large offices, other services). The retrofits include operations and maintenance, lighting, ventilation, envelope measures, water heating, load management, and others. The economic data are available for a subset of 134 buildings with electricity-saving retrofits. See the reference for general information and results; additional electricity-specific data are from Kathy Greeley and Mary Ann Piette, Lawrence Berkeley Laboratory, memorandum of November 9, 1987.



Savings in this scenario are derived from a combination of building envelope and heating system retrofits, plus fuel switching. For this purpose, we segment the stock into four parts, based on annual surveys by the national bureau of statistics in Sweden. The first segment has electric resistance heating and no ability to use an alternative fuel. The second segment heats with hydronic electric-only systems. Other buildings use electric heat pumps. The fourth segment currently has the ability to heat with two or more fuels, including electricity.<sup>11</sup>

To estimate penetration in households, we assume, as in the Reference Scenario, that 10% of the homes do nothing whatsoever. For those remaining: electric-resistance homes install insulation and upgrade their glazing if other renovation work is performed (27).<sup>12</sup> The very-high-use homes (>30,000 kWh/year) install ground-source heat pumps (COP 2.7); homes with electric-only boilers install heat pumps; homes that can switch fuels are assumed to do so or to install heat pumps.

To be conservative, we assume that all new homes use electric heating. These homes conform to the state-of-the-art performance described in the chapter by Elmroth.<sup>13</sup> Triple-pane windows with coatings or gas fill, described in (28), are included in new energy-efficient homes in the scenario. The current Swedish construction standard requires triple-glazing, but not coatings or gas fill.

We do not analyze envelope efficiency improvements in buildings that switch fuels. There is a potential quick increase in electricity demand due to re-conversion if the electricity-to-oil price ratio for any reason decreases (and policies do not respond).

<sup>11</sup> All base-year values for electric heating are 1987 consumption, normalized to average-year weather conditions (Personal communication, Anders Sjögren, Vattenfall, January 15, 1989).

<sup>12</sup> According to Elmroth's chapter, of all homes heated with electric-resistance systems and constructed before 1982, only 25% of the window area (6.57 million square meters) is triple-glazed. Roughly 1% of the area is single-glazed windows and 1% is quadruple-glazed. Even more remarkable, only 60% of the window area installed between 1975 and 1981 was triple-glazed.

<sup>13</sup> According to the Reference Scenario, the increased consumption for single-family homes is 1.7 TWh/year by 2010. Were all of these homes heated at the efficiency described in Elmroth's chapter (2,500 kWh/y for space heating and 2,500 kWh/y for water heating) the resultant demand growth would be 1.1 TWh.

## 2.2.4 High-Efficiency Scenario

In this scenario, we assume (in addition to the previous scenario) slightly more effective lighting system retrofits in services and industry, adjustable-speed drive applications, and several advanced household appliances that are not commercialized at this time but can be designed using existing components. Heat pump COPs increase from 2.7 to 3.3 based on (29). We make a special scenario for steel, based the Plasmascrap process described in (30, 31). Plasma beam heating is discussed more generally in (32). Conversions to natural gas in industrial process heating increase from 2.1 to 2.8 TWh<sub>e</sub> in 2010.

## 2.2.5 Advanced-Technology Scenario

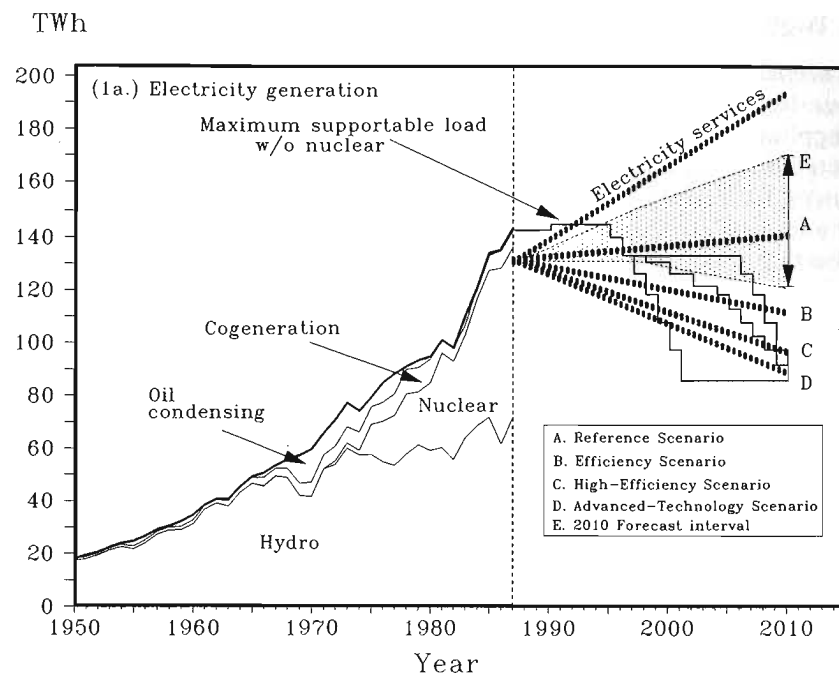
The final scenario makes use of measures that are technically possible but can not necessarily be judged cost-effective at present. We convert to oil and conserve a total of 0.5 TWh of electric heating in vacation homes; (out of a total of 2.4 TWh), 0.5 TWh of electricity used in large heat pumps, and an additional 1 TWh of electric heating in single-family homes. In the steel industry, we assume the introduction of direct casting (33) which saves 1.3 TWh by eliminating 75% of the estimated need for motor power in the rolling process.

## 2.3 Electricity Demand Results

### 2.3.1 Overview

The level of electricity services corresponding to the Frozen-Efficiency baseline is equivalent to 194 TWh/year by 2010. The Reference Scenario estimates generation at 140 TWh<sub>e</sub> – which means that 54 TWh<sub>eq</sub> equivalent of the required services will be provided with increased end-use efficiency and alternate fuels. In the Efficiency, High-Efficiency, and Advanced-Technology Scenarios, electricity generation falls to 111 TWh, 96 TWh, and 88 TWh, respectively.

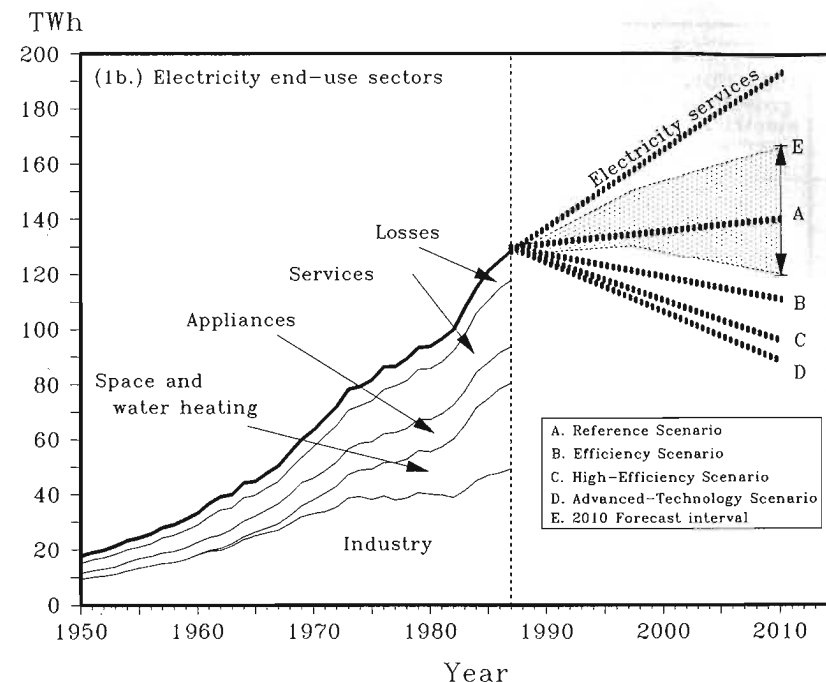
The historic and projected sectoral components of total supply and demand are shown in Figures 1a and 1b. In light of the policy to phase Sweden's nuclear plants out of operation by 2010, the question immediately arises as to when new capacity will be required. The stepped curves in Figure 1a reflect



Figures 1a and 1b. Historic electricity generation and demand scenarios for the future. Figure 1a shows the evolution of Sweden's generation mix up to 1987. Peaking turbines have provided only about 0.1 TWh/year since the late 1960s. The three stepped curves represent the range of proposed schedules for phasing out Sweden's 12 nuclear reactors. The curves show the level of electricity demand acceptable with the current system reliability levels and no new capacity additions. The small vertical gap between 1987 and the scenario starting point represents interruptible power. As shown in Figure 1b, since the beginning of the nuclear building period, electric space heating has risen from almost zero to over 30 TWh/year.

three possible nuclear phase-out programs.<sup>14</sup> The middle case reflects a linear phase-out plan, and faster and slower cases are included for comparison. These three curves have clearly distinct impacts on the schedules for the construction of new generating capacity, which is required when demand falls below the stepped curve.

<sup>14</sup> The curves represent today's hydro and fuel-based generation plus that from the nuclear plants remaining in each year of the period up to 2010, at which time nuclear generation will be zero. The height of the curves includes today's accepted reliability margin, using the rule of thumb that the maximum tolerable demand =  $0.80 \times \text{hydro production potential} + 0.90 \times \text{thermal production potential}$ . (Environmental restrictions will require additional investments in the existing fuel-based power plants if they are to be used much more heavily than is the case today.)



The sectoral breakdown for each of the four scenarios is shown in Figure 2. Additional detail on the sector-specific supply of electricity is shown in Table 1 and in Figures 3 through 6. Following are some key observations for each sector, and the overall reduction in specific needs (Efficiency, High-Efficiency, and Advanced-Technology Scenarios):

- Substantial increases in efficiency occur in the household appliances sector. Yet structural changes (increased numbers of appliances) offset much of the savings. Food storage appliances offer perhaps the greatest efficiency potential. Overall specific needs decline to 66%, 47% and 47% of their 1987 levels.
- In the service sector, demand falls, due mostly to improvements in existing buildings. New buildings represent 15% of the total floor area in 2010. The greatest efficiency gains are in motors, etc., and in lighting. Overall specific needs decline to 50%, 44% and 44% of their 1987 levels.
- In the industrial sector, electricity demand in the Efficiency Scenario remains about the same as in 1987. Motors, fans, pumps, etc., are by far the most important end-use (64% of all industrial electricity in 1987) and paper and pulp is by far the most important sub-sector. Overall specific needs decline to 70%, 60% and 53% of their 1987 levels.

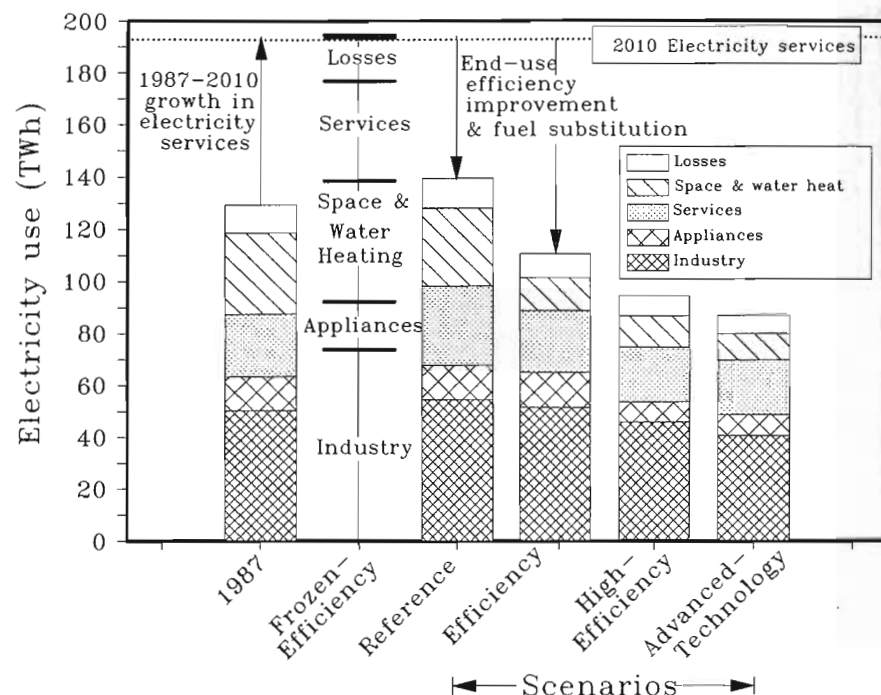


Figure 2. Total electricity demand plus losses for 1987 and for the four scenarios in 2010. The level of electricity services supplied (from the Frozen-Efficiency calculations) is shown as the horizontal dotted line. The height of the bars represents electricity use and the gap between the top of each bar and the horizontal line represents the electricity services provided with efficiency improvements and fuel substitution.

- Existing fuel and equipment flexibility in the space heating sector contributes to substantial electricity reductions via fuel substitution and the use of heat pumps in existing hydronic systems. The Reference Scenario also includes conversions to electricity of 3 TWh<sub>e</sub> (because a crude oil price of \$30/barrel is assumed). The Efficiency Scenario incorporates 6.9 TWh<sub>e</sub> of fuel switching in buildings, which would increase Sweden's 1987 total oil imports by 4%.<sup>15</sup> Overall specific needs decline to 39%, 37% and 32% of their 1987 levels.
- Transmission and distribution losses are 9.2 TWh in the Efficiency Scenario, versus 10.6 TWh in 1987. Both numbers are based on losses equal to 9% of demand.

<sup>15</sup> Based on an oil boiler efficiency of 80%.

Table 1. Summary statistics for the scenarios.

TWh <sub>e</sub>	1987	2010	Average %/y growth rates (23 yrs)
<i>Frozen-Efficiency baseline</i>			
Industry	49.3	73.9	1.8%
Household appliances	13.2	18.1	1.4%
Services	24.2	46.9	2.9%
Space and water heating <sup>a</sup>	31.3	38.7	0.6%
Losses	10.6	16.0	1.8%
Total	128.6	193.6	1.8%
<i>Reference Scenario</i>			
Industry		54.2	0.4%
Household appliances		13.2	0.0%
Services		30.5	1.0%
Space and water heating		30.0	-0.2%
Losses		11.5	0.4%
Total		139.5	0.4%
<i>Efficiency Scenario</i>			
Industry		51.4	0.2%
Household appliances		11.9	-0.4%
Services		23.5	-0.1%
Space and water heating		14.9	-3.2%
Losses		9.2	-0.6%
Total		110.9	-0.6%
<i>High-Efficiency Scenario</i>			
Industry		44.2	-0.5%
Household appliances		8.5	-1.9%
Services		20.7	-0.7%
Space and water heating		14.5	-3.3%
Losses		7.9	-1.3%
Total		95.9	-1.3%
<i>Advanced-Technology Scenario</i>			
Industry		39.0	-1.0%
Household appliances		8.5	-1.9%
Services		20.7	-0.7%
Space and water heating		12.5	-3.9%
Losses		7.3	-1.6%
Total		88.0	-1.6%

<sup>a</sup> In 1987, the end use shares were: single-family homes (61.0%), multi-family homes (14.3%), vacation homes (6.3%), services (10.4%), municipal heat pumps for district heating (8.0%). Values may not add perfectly due to rounding errors.

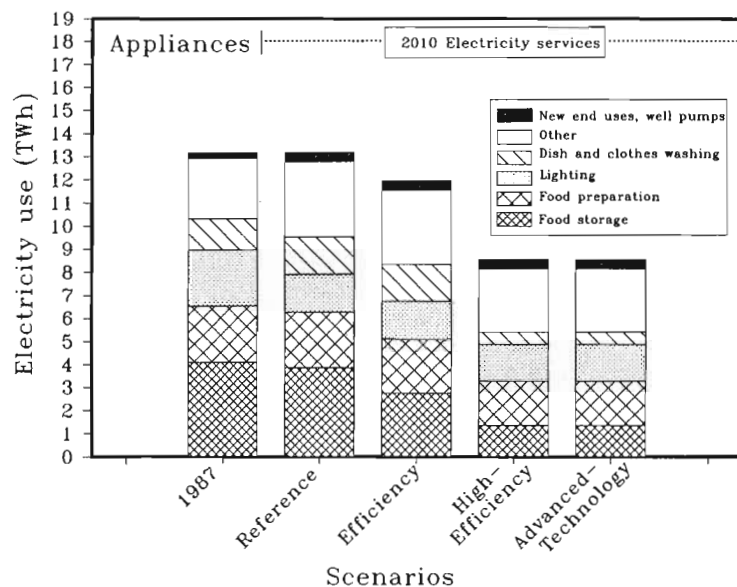


Figure 3. Residential appliance electricity demand results for 1987 and for the four scenarios in 2010. Six end-uses are shown.

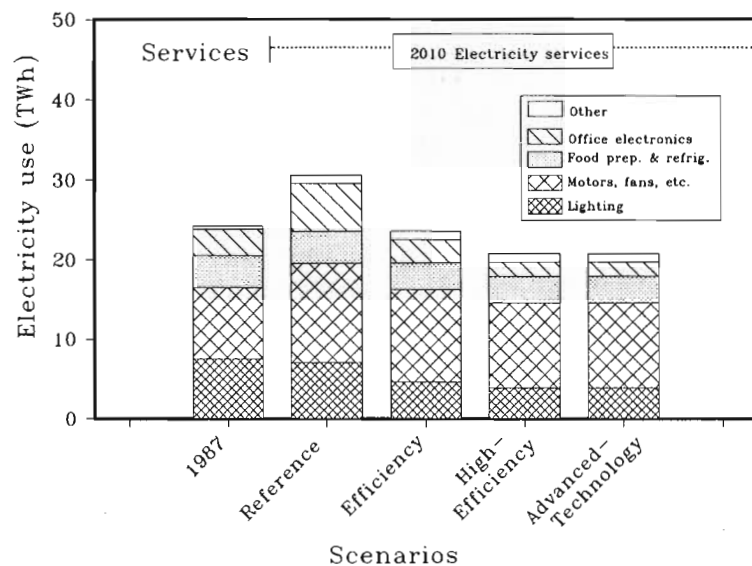


Figure 4. Service sector electricity demand results for 1987 and for the four scenarios in 2010. Five end-uses are shown.

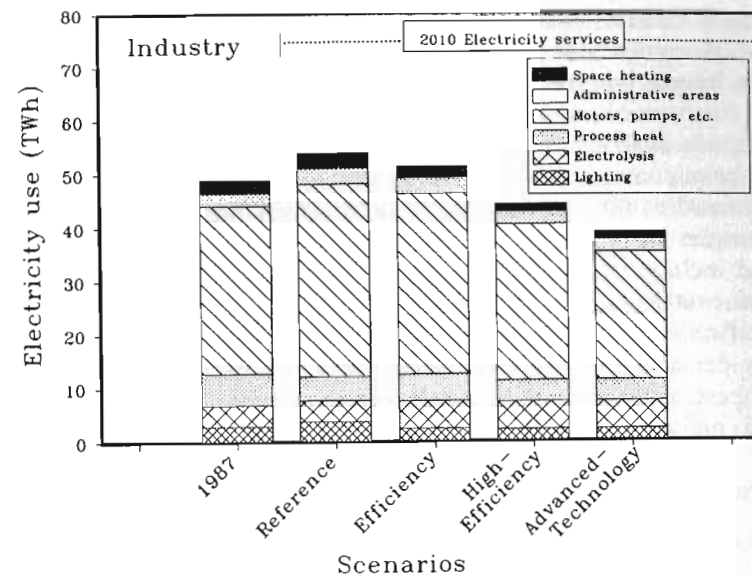


Figure 5. Industrial sector electricity demand results for 1987 and for the four scenarios in 2010. Six end-uses are shown.

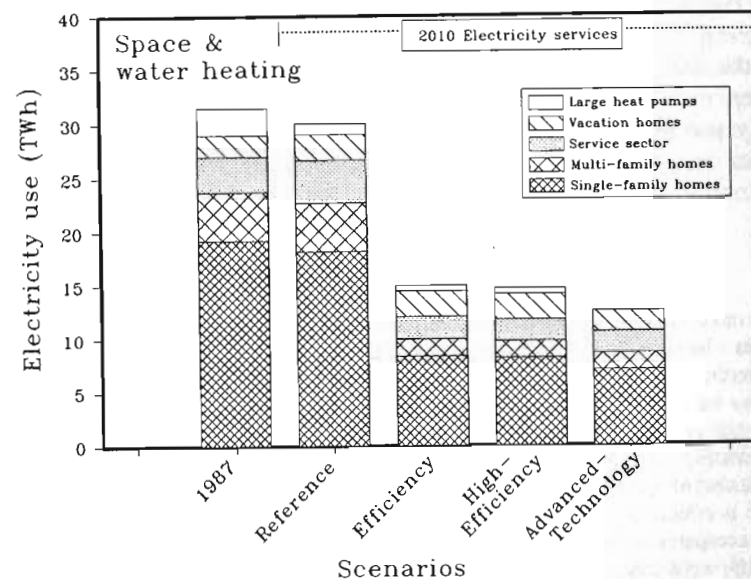


Figure 6. Space and water heating electricity demand results for 1987 and the four scenarios. Five sub-sectors are shown. The main source of the difference between the Reference and the two Efficiency Scenarios is fuel switching and use of heat pumps.

Our results are consistent with those from a number of other similar studies in Nordic countries and elsewhere. Recent scenarios made for Denmark resulted in overall end-use electricity intensities at 66% of the 1986 level for presently commercialized technology and 51% for advanced technologies that could be made available within 10 years (34). A similar, and more detailed, study has been completed for Finland (35). The authors identify a potential to reduce demand to 60% of the level forecasted for the year 2020. There are many examples from the United States, most of which focus on the residential sector and include both energy and peak-demand potentials (36, 37). At the State level, studies have been done for Michigan (38), Texas (39), the four-state Pacific Northwest Region (40)<sup>16</sup> and California (41, 42). Studies of electricity demand potentials have also been conducted in Canada (43, 44). Many of these analyses employ supply curves of conserved electricity to rank the various conservation measures in order of levelized cost per kilowatt-hour.

### 2.3.2 Efficiency economics

For most demand-side technologies in the Efficiency Scenario, we used the cost of conserved electricity (CCE) statistic to calculate cost effectiveness.<sup>17</sup> The CCE is the annualized investment in increased efficiency (and incremental operations and maintenance, if any) divided by the annual reduction in electricity use required to provide the same service. Thus, the result has the same units as the price of electricity (cents/kWh) and can be easily compared

<sup>16</sup> Perhaps most relevant to the Nordic situation, this study evaluated the electric demand-side potentials in a large hydropower-based region of the Pacific Northwestern United States where a large generating company sells power to many small distributors. This study determined that the base case forecast of residential sector demand by the year 2000 (7,728 average megawatts) could be reduced to 58% of their forecasted levels if all technically feasible conservation measures costing less than 15 cents/kWh were implemented. Of this total, 87% could be realized at a cost of 4 cents/kWh.

<sup>17</sup> The CCE is effectively a "busbar" cost indicator for conservation technologies and can thus be directly compared with levelized cost (fixed + variable) of new electricity supply. To ensure compatibility, we account for the reinvestment costs if efficiency technologies must be replaced during the 30-year economic lifetime of a reference power plant. (Note: the economic calculations in this chapter are based on 1987 US dollars. We use a 6% real discount rate to determine the choice of end-use strategies, except in the Reference Scenario where consumer investment behavior corresponds to a significantly higher discount rates.)

with retail prices or with the busbar cost of new supply.<sup>18</sup> Table 2 summarizes the results. Note that several measures are shown at zero cost because they involve fuel switching. The cost of the new fuel is counted instead in the final economic assessment in Section 4.

From the table, we can see that substantial cost-effective efficiency resources are available in Sweden, i.e., are available at a fraction of the cost of new electricity supply. In Section 4.1 the demand-side resources we have identified will be ranked along with electricity supply technologies in a grand supply curve for the year 2010.

Although capital investment is commonly required to achieve savings, some efficiency-improving technologies can increase electricity efficiency at zero or even negative cost. This can result from:

- 1 gains derived from no- or low-cost changes in operations of existing technology,
- 2 more careful selection among appliances available in the marketplace,
- 3 technological change that has a "side-effect" of improved efficiency,
- 4 reductions in labor and/or replacement costs that exceed the investment, or
- 5 complex engineering interactions that create "bonuses" by reducing the energy demand in an end-use other than that targeted with the efficiency technology.

Today's marketplace for refrigerators and freezers in Sweden provides a clear example of the sometimes imperceptible incremental cost for selecting the best-available appliances (point 2 in the list above). As shown in Figures 7a to 7c, there is no correlation between the price and the energy efficiency of refrigerators in Sweden.<sup>19</sup> This also holds for freezers and combination refrigerator/freezers.

<sup>18</sup> For a given pool of electricity consumers that make investments to increase end-use efficiency, there will be a range of costs and savings. Thus, one can envision a corresponding distribution of costs of conserved energy. From a societal perspective, over-investment in efficiency may occur if some participants in the right-hand tail of this distribution have CCEs higher than the cost of new energy supply. This risk is low when the average CCE is itself well below this "break-even" cost and can be further minimized by careful definition of the "target group". Some analysts allow the more economic projects to "carry" the less economic ones, but our methodology is to judge each investment on its own merits.

<sup>19</sup> Mills, E. 1988. *Energy and the marketplace for residential appliances in Sweden*. Department of Environment and Energy Systems Studies. Lund University. Manuscript in preparation. Scatter diagrams of retail price versus total annual electricity use also show little or no indication of an extra cost for higher efficiency. This is true even within narrow size ranges (e.g., among 200-250 liter models). We have observed the same result for residential clothes washers and for stand-alone domestic water heaters.

Table 2. Selected cost-effectiveness calculations for the Efficiency Scenario.

End-use technology or strategy	Annual savings (TWh)	Cost of conserved or switched electricity (cents/kWh) <sup>a</sup>
<i>Measures requiring incremental investment</i>		
Lighting (all sectors) <sup>b</sup>	12.0	
compact fluorescents (3000 h/y) <sup>b</sup>		1.0
fluorescent systems (2000 h/y) <sup>b</sup>		1.6
Motors & pumps, compressors, etc <sup>c</sup>	18.5	1.4
Commercial food refrigeration <sup>d</sup>	2.4	2.5
Residential heat pumps <sup>e</sup>	5.7	
of which electric resistance home <sup>e</sup>	(2.0)	6.8
of which electric boiler home <sup>e</sup>	(3.7)	4.5
Appliances (excl. lighting) <sup>f</sup>	5.1	0.6
Subtotal	43.7	1.9
<i>Measures requiring little or no investment</i>		
New home construction <sup>g</sup>	0.6	very low
Miscellaneous office equipment <sup>h</sup>	6.4	very low
Large heat pumps <sup>i</sup>	2.0	0.0
Fuel switching for space heating <sup>j</sup>	6.9	0.0
Transmission & distribution losses <sup>k</sup>	6.8	0.0
Subtotal	22.6	
Total	66.3	1.2
Residual non-monetized savings <sup>l</sup>	16.3	?

<sup>a</sup> Electricity savings are measured here as the difference between the Frozen-Efficiency Baseline and the Efficiency Scenario results. Fuel substitution is shown at zero cost because there is no capital cost and the costs of the alternate fuels themselves are counted instead in Section 4.2. For lighting, the simple average of the two values shown is used. All CCEs are comparable to the levelized cost of a power plant with a 30-year economic life and 6% real discount rate. The weighted average excludes the TWh in the last row.

<sup>b</sup> For compact fluorescents, the lifetime of an improved lamp is 10,000 hours (14-Watt), versus 1,000 hours (60-Watt) for the replaced lamp. Thus, 10 incandescents need not be purchased. We assume a retail price of \$10 for the high-efficiency Satco lamp (45) and an avoided cost of \$0.80 for the incandescents. These costs represent recent prices in the U.S., which have fallen by more than a factor of two in just a few years. A similar development should occur in Sweden. For ballasts, we assume 260 8-hour days/year operation, plus costs and savings according to the case study in (46).

<sup>c</sup> Capital costs from ABB Corporate Research (personal communication, Lars Gertmar, December 15, 1988) and represent costs relevant to the Swedish setting: \$296/kW (18.5 kW motor) and \$104/kW (750 kW motor). Installation costs assumed at 23% of capital costs for the

small drive and 8% for the large drive. A 15-year lifetime is also assumed in the calculations (47). The corresponding CCEs for 3,000 and 4,000 hours/year are 2.3 cents/kW and 1.8 cents/kWh, respectively. In his chapter, Baldwin suggests substantially lower installed costs: on the order of \$100/kW.

<sup>d</sup> Savings result from a combination of measures described in (48). The costs of conserved energy are the average from the following list: retrofit glass doors, plastic curtains, unequal compressor systems, variable-speed drives, and floating head pressure controls.

<sup>e</sup> Earth-source heat pumps with closed-loop working fluid. Applied to high-use electric-resistance homes (parts/labor \$13,500) and to average multi-fuel homes with pre-existing storage/distribution systems (\$9,400) (49). COP assumed = 2.7; lifetime 15 years.

<sup>f</sup> The CCE is the average for all appliances from the chapter by Nørgård in this volume (50).

<sup>g</sup> The average electrically-heated home in the stock uses approximately 17,000 kWh/year for space and water heating (and this is the frozen-efficiency assumption), and the current building Norm results in 8,000 kWh/year (Elmroth's chapter in this volume). Most of these savings beyond the Norm (3,000 kWh) come at little or no incremental cost.

<sup>h</sup> The savings estimate is based on technological changes that are happening naturally in the marketplace. The chapter by Norford *et al* refers to several examples where incremental costs in today's marketplace are zero.

<sup>i</sup> Assumes that some large heat pumps are not replaced at the end of their useful lifetime.

<sup>j</sup> Fuel switching assumed to occur at zero capital cost because we consider only homes with multi-fuel systems. The total cost for heating energy declines as a result of switching. In some homes an investment might be required, for example, to revitalize oil burners. Electricity prices from the Reference Scenario provide a strong incentive to switch fuels during on-peak times: 11.1 cents/kWh on-peak electricity, 5.4 cents oil.

<sup>k</sup> Transmission and distribution losses (9% of generation) are reduced because total demand is reduced. There is no additional cost for these savings.

<sup>l</sup> The residual includes industrial process heat (3.4 TWh); industrial space heating (2.3 TWh); industrial electrolysis (0.9 TWh), triple-pane or low-e windows (0.3 TWh), residential building envelope retrofits (1.4 TWh), commercial buildings construction (2.5 TWh) [Commercial buildings are constructed based on an estimate from the chapter by Abel in this volume. The performance target is arrived at on the basis that it is cost-effective from the perspective of the building owner]. There is no reason to assume that the CCEs for these measures are higher than those for the other measures in the table.



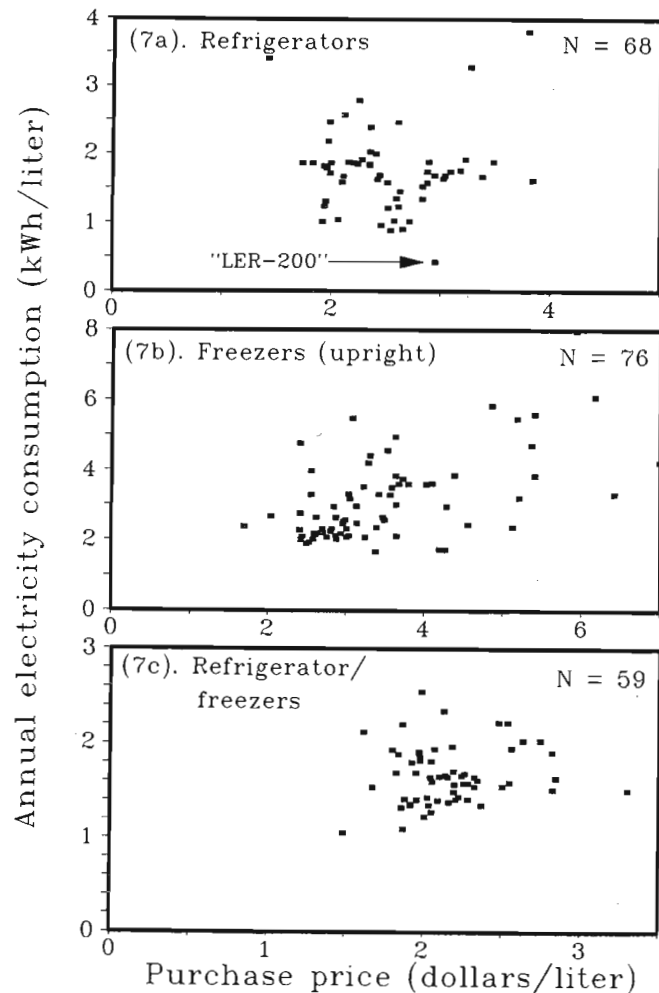


Figure 7a-7c. The non-correlation between appliance retail price and energy-efficiency. Each data point is a refrigerator, freezer, or combination refrigerator-freezer model sold in Sweden as of August 1987. Note that for a single price level, efficiency, measured as kWh/liter-year, can vary by a factor of two or three.

Each model is government-tested according to a standard procedure (25°C ambient, no door openings, no auto-defrost cycle). To compensate for varying freezer volumes in refrigerators with small freezer compartments and in combination units, freezer volumes are adjusted to their refrigerated-volume equivalents according to the U.S. Department of Energy testing methodology. No such adjustment is made for freezers. A number of specialty models are excluded. The 200-liter Danish LER-200 (now marketed in Denmark by Brdr. Gram A/S) is shown for reference. A model of nearly identical size and price, but with twice the electricity use, is made by the same manufacturer.

### 2.3.3 Electricity and economic well-being

Assuming that Sweden's GDP continues to grow at 1.9%/year, electricity demand would decline at 0.6%/year, according to the Efficiency Scenario. Thus, the ratio of electricity use to GDP would decline sharply while economic growth continues.<sup>20</sup> Sweden, like Canada and Norway, has enjoyed relatively low electricity prices and, partly as a result of this situation, many electricity-intensive industries and widespread use of electric space heating in their cold climates have contributed to a high level of electricity use. However, assuming the development shown in the Efficiency Scenario, Sweden's 2010 electricity intensity will be similar to today's values for many other industrialized countries, as shown in Figure 8.<sup>21</sup>

Comparisons of electricity use per capita are also interesting. In 1987, the intensity was about 17,400 kWh/capita. This may be compared with that of Japan (5,600 kWh/capita), West Germany (6,700 kWh/capita), or the U.S. (11,000 kWh/capita). The comparison is shown in the left-hand set of bars in Figure 8 for the OECD as a whole and for 13 member countries.

Figure 9 puts each of the four scenarios in perspective with historic electricity demand and GDP. An interesting characteristic of the Frozen-Efficiency baseline is that the aggregate result for all sectors show electricity use per unit of GDP as almost the same in the year 2010 as in 1987. This is in line with our assumptions insofar as electricity use per GDP can be considered a measure of national electricity use. This implies a break in the historic trend of increasing electricity use per unit of economic activity. This comes about because of structural changes in the economy towards less electricity-intensive activities, and in much-reduced growth in electric space heating. In the 2010 Reference Scenario, electricity/GDP has fallen by 30%; in the Efficiency Scenario it falls by about 50%.

### 2.3.4 Factors that could lead to other scenarios

No forecast or scenario can incorporate every determinant of energy use, nor can it account for all of the possible permutations of its assumptions. The scenarios in this chapter are constructed within a given set assumptions about the economy and about technologies. Following is a list of factors that could contribute to scenarios of either higher or lower electricity use. Some factors

<sup>20</sup> Gross domestic product statistics from (51) through 1980. Data for 1981 to 1987 are from (52). For the 1987 to 2010 estimate, we use the standard 1.9% annual growth estimate.

<sup>21</sup> Decoupling of electricity and GDP is occurring in some other industrialized countries. See Rosenfeld & Koomey (53) for an illustration of trends in the United States.

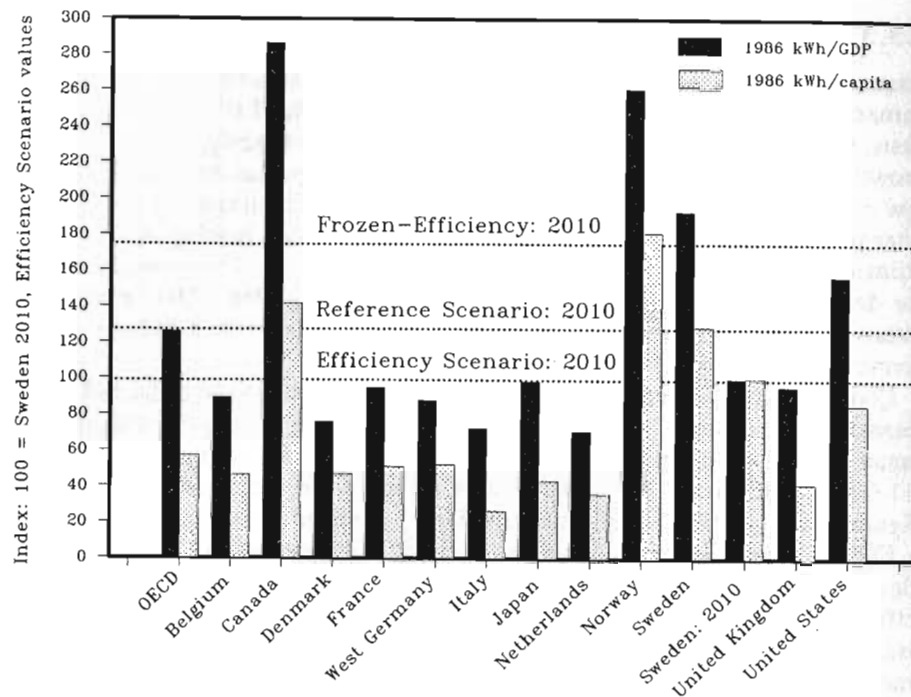


Figure 8. Comparison of electricity intensity (measured as kWh/capita and kWh/GDP) in the Efficiency Scenario with that of other industrialized countries. The results for Sweden in 2010 are transformed into an index = 100 (third pair of bars from the right). Sweden's intensities in 1986 as well as those in the other countries are thus compared with the Swedish 2010 values. Horizontal lines for two other 2010 demand levels – relative to the Efficiency Scenario – are also shown.

reflect differences in energy service levels that would be associated with different developments of society and the economy:

- Alternate levels of energy services demanded by consumers
- Alternate GDP growth trends
- Changes in lifestyle other than those assumed in the structural and utilization factors in the appliance model and implied in the growth of electricity services in the Frozen-Efficiency baseline for the service sector
- Alternate levels of immigration and domestic population growth
- Different patterns of structural change in industry, e.g., a larger shift to more electro-mechanical pulping in the paper and pulp industry, than the 44% increase in production assumed in the scenarios

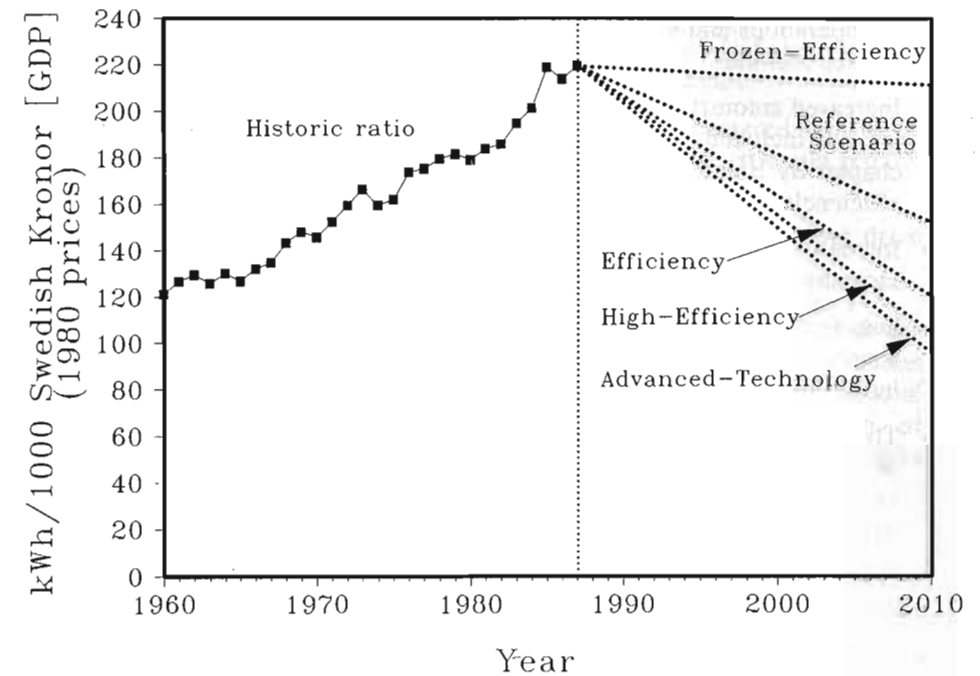


Figure 9. Translation of the scenario results into overall national efficiency trends. Here, efficiency is defined as electricity use per unit of gross domestic product. The historic trend shows how electricity use increased much more rapidly than overall economic growth up to 1987, due in part to the steady growth of electric heating. All scenarios are based on annual GDP growth of 1.9%. The values shown exclude interruptible power, up to 10 kWh/1000 kronor in recent years.

Other factors relate to the end-use technologies. The Efficiency and High-Efficiency scenarios are conservative insofar as a less-than-exhaustive list of efficiency technologies and strategies are included. There are many unexplored efficiency opportunities. The factors that could reduce electricity use further than in these scenarios include:

- Technological change can bring entirely new efficiency opportunities, e.g., aerogel window materials or electrochromic smart windows discussed in the chapter by Granqvist. Only a few such improvements are included in the Advanced-Technology Scenario.
- One-half of the double-paned windows in electric-resistance homes are upgraded to triple-glazing, but only those constructed up to 1981. Greater savings could be attained by installing a third pane treated with a low-emissivity coating.

- No operations-and-maintenance measures are included for the industrial and service sectors.
- Increased automation and controls can save large amounts of electricity but are not included here. Power-integrated Circuits (PICs), described in the chapter by Baldwin, will lead to a new generation of “smart motors” with efficiencies above those we have assumed (54).
- Increased use of pollution controls can reduce waste and thus indirectly increase efficiency due to increased material productivity.
- Due to lack of data on the existing stock, no low-cost measures such as water-efficient showerheads and thermostat controls are included. Also not included are heat pump water heaters.
- The only building insulation retrofits considered are those in homes heated with electric-only systems. Not only might additional retrofits be cost-effective in other buildings, but would also reduce the risk of unexpected demand growth if multi-fuel homes re-convert to electric heating.
- Except for the Advanced-Technology Scenario, no electric space-heating savings potential is assumed for vacation homes.
- No fuel-switching is assumed for residential electric appliances although a potential exists (stoves use 1.4 TWh, clothes washing and drying use 1 TWh, and water heating uses about 5 TWh in the Reference Scenario). No natural gas substitution is assumed for commercial cooking equipment.
- Air conditioning is an emerging end-use in new and existing service-sector buildings. We assume no efficiency improvement, although many options exist (55).

Just as the factors described above could contribute to efficiency gains beyond those incorporated in our scenarios, a similar list may be constructed to enumerate factors that could work to push demand upwards:

- Technological change could introduce new electricity end-uses or processes, e.g., microwave drying of lumber in industry.
- Of the buildings that have converted from electricity to fuel, some could later convert back to electricity for heating following higher fuel prices and the absence of balancing policies. The size of this “virtual load” is 6.9 TWh, in the Efficiency Scenario.
- We have incorporated only to a small extent the “take-back” of electricity savings in the form of increased energy services, e.g., increased lighting intensity or lamp on-time, higher interior temperatures, larger refrigerators, etc.

- Persistence of savings. The deterioration of technology efficiency has been taken account of in the residential appliances model (refrigerator and freezer efficiency declines by 1% annually) but not elsewhere.
- Increased utilization of pollution control equipment or increased ventilation to make “buildings healthier” over what is already assumed could require additional electricity use.
- Additional waste-heat recovery in industry could conserve fuel but drive electricity use upwards more than assumed.

There are distinct differences in the potential magnitude of impacts from the uncertainties in the factors listed above. Uncertainties related to the factors pertaining to the development of society as a whole could lead to scenarios of significantly higher or lower electricity demand. The latter two groups of factors – concerning specific technologies and their performance – would affect national electricity use less.

## 3 Electricity/Heat Supply Scenarios

### 3.1 Methodology

In this section, we develop electricity supply and heat scenarios to couple with the demand scenarios described above. We take the same conceptual approach to supply-side technology as we did in our demand-side analysis. Here the goal is to illuminate some of Sweden’s supply options by incorporating best-available technologies as well as some which are still in the research and development phases but could be brought to the market well within the time-frames of a 1987-2010 planning period. We adhere to the system boundary, described earlier, that includes all of the services today provided by electric heating and other electric end-uses, industrial cogeneration of electricity and process heat, and district heating.

An important objective in electricity planning is to obtain a production system that supplies power at the lowest possible cost, given the accepted reliability requirements.<sup>22</sup>

<sup>22</sup> The maximum acceptable loss of load probability (LOLP) criterion in Sweden is 0.1 percent (9 hours per year over the entire system) and the maximum risk of energy shortage criterion is 3.0 percent (rationing will occur 3 years out of 100). Historically, LOLP has been very low in Sweden, thanks to the large share of hydro power in the system. However, the thermal power share has increased due to the nuclear program and along with it the issues of reliability. The

The stepped curves shown in Figure 1a show Sweden's current reliability criterion and the generating capacity available in Sweden as the nuclear plants are phased out. The planning task is to bring new generating capacity on-line by the year that the demand curve drops below the stepped curve. Depending on the assumed demand scenario and which phase-out schedule is assumed, new capacity would be required sometime between 1995 and 2010.

For new capacity, we utilize technology relevant to the Swedish context. To account for existing generation capacity, we use costs reported by Vattenfall and from the literature.

The integrated nature of heat and power production necessitates the explicit inclusion of district heating in our analyses. We assume that municipal district heating demand in 2010 is the same as that in 1987 (38 TWh<sub>th</sub> including losses). This is based on efficiency improvements in existing buildings being offset by the entry of new customers. The district heating today provided by refuse-derived fuels (RDF) incineration, waste heat, grey-water heat pumps, etc., (5 TWh, or 13% of the total) is included in the preceding estimate. In industry, we include 15 TWh of industrial process heating, to be provided by a mixture of cogeneration and boilers.<sup>23</sup> The electricity production cost for a year is credited for the heat sales from cogeneration during the year (i.e. 35 TWh in the scenarios).

## 3.2 Electricity Supply Technologies

This section briefly describes the existing generating mix and various generation options and their economics. The variable cost estimates indicated for today's capacity are those used by Vattenfall.

### 3.2.1 Condensing power

Today's non-nuclear condensing power in Sweden is based on oil. There is currently a generation capacity for 20 TWh/year, but less than 1 TWh is typically utilized. The variable cost of this oil-fired capacity is 3.9 cents/kWh.

generating capacity, upon which reliability calculations are based now permits a demand level of 145 TWh/year (including the Vattenfall convention of including 5 TWh of imports) based on these criteria. The reliability factors are commonly summarized using the rule-of-thumb that demand must not rise above the level, defined in footnote 14.

<sup>23</sup> For district heating provided with natural gas fuel, we assume the current cost in Sweden of 2.7 cents/kWh. To this we add 0.35 cents/kWh to account for the transmission system cost (Vattenfall estimates, 85% boiler efficiency).

There are currently no gas- or coal-fired condensing power plants in Sweden. The total busbar costs for constructing and operating coal- and natural gas-fired plants in Sweden are estimated at 4.2 cents/kWh.

### 3.2.2 Combined heat and power (CHP) and industrial cogeneration

Today there is an installed CHP capacity in district heating systems of 6.5 TWh<sub>e</sub>/year, and about half of this is utilized based on a mixture of oil and solid fuels (peat and coal), with a variable costs of 1.7 cents/kWh<sub>e</sub>. The busbar costs for new capacity are estimated at 3.2 cents/kWh<sub>e</sub> in Sweden. Pressurized fluidized bed combustion (PFBC) systems may provide both electricity and useful heat while emitting less sulfur oxides than in conventional coal-fired power systems. Discussion of the state-of-the-art in PFBC is provided by Pillai in this volume (56).

Industrial backpressure cogeneration systems have been in the Swedish system since before 1950. Today's installed capacity can produce 5 TWh<sub>e</sub>/year, much of which is in the paper and pulp industries. Production in 1987 was 3 TWh and the variable production costs are 1.6 cents/kWh. We estimate the total busbar cost at 3.1 cents/kWh.

Steam-injected gas turbines (STIG) fueled with gasified biomass could potentially supply large quantities of power and heat in Sweden. As described in the chapter by Larson *et al.* (57), such systems can be configured with absorption heat pumps or as combined cycles to attain relatively high overall efficiencies. The total busbar costs of electricity generated by biomass-gas driven turbines for Sweden are estimated at between 4.5 and 5.6 cents/kWh, assuming fuel prices of \$3/GJ including the costs of drying, chipping, and delivery to the power plant. This range is based on an avoided fuel cost of \$2.0-\$5.0/GJ in determining the heat credit; the natural gas prices in Box 1 correspond to about \$3/GJ. In our analysis, we assume a higher fuel cost of \$3.6/GJ (58, 59) and that the busbar cost of this option will be 5.6 cents/kWh.

Due to the small size of many district heating systems in Sweden, turbine systems smaller than the 53 MW<sub>e</sub> ones assumed in these calculations would have to be used in many cases. A similar situation holds for the 25 MW<sub>e</sub> circulating fluidized bed (CFB) coal systems that we specify for cogeneration. For the biomass CHP systems, this effect increases the capital cost by up to 60% (at 5 MW<sub>e</sub>), or ~0.7 cents/kWh. However, a higher heat credit is also attained by smaller systems and this will partially offset the cost increase. This effect is much smaller than the 50% increase of total busbar costs that we calculate in a sensitivity analysis of biomass cost in Section 4.2.

### 3.2.3 Gas turbines

The installed capacity in the Swedish system is currently 1,800 MW. These oil-fired turbines are used as peaking capacity only. Total busbar costs are 9.7 cents/kWh.

New technologies make it possible to use natural-gas-fired turbines in baseload applications. The steam-injected gas turbines (STIG) and intercooled steam-injected gas turbines (ISTIG) described by Williams & Larson in this volume have busbar costs that are competitive with traditional generating technologies and can be used in electric-only or combined heat and power configurations (60). Advanced gas-fired combined cycles are also an important technology, and may be based on natural gas, gasified coal, or gasified biomass.

### 3.2.4 Wind power

Sweden has sufficiently strong winds to institute the increased use of wind power. Land use restrictions favor the use of offshore plants. Cost estimates vary widely, depending on siting and the quality of the wind resource at the site. Experimental wind stations exist and provide some indication of the investment requirements.

According to a recent governmental committee report, sites have been identified that would permit a generation of 1.5–7 TWh/year at land-based sites and 22 TWh/year offshore (61). However, this report does not include any economic analysis. Vattenfall's current belief is that the likely utilization of wind is 0–3 TWh/year at a cost of 7.0 cents/kWh.<sup>24</sup>

### 3.2.5 Fuel cells & photovoltaics

Electricity and heat could be provided with fuel cells during the scenario time frame. Also, photovoltaic solar cells could perhaps provide some electricity during the summers late in the scenario time frame. The chapters by Blomen and Carlson discuss the state of the art and prospects for the future (62, 63).

<sup>24</sup> The estimated cost interval is 6.3–7.9 cents/kWh (personal communication, Göran Svensson, Vattenfall, February 10, 1989).

## 3.3 Resource Constraints and Potentials

Many new types of power generation systems could be constructed in Sweden. The introduction of systems based on natural gas is constrained by gas availability, prices, and the current lack of a gas transport network.

The potential for biomass-fired generation is also constrained by fuel availability. Approximately 50 TWh/year of existing presently unused biomass fuel could be recovered and utilized for power generation (64, 65). Gasified and then converted to electricity and heat in gas turbines, this resource could generate ~15 TWh of electricity and ~15 TWh of district heating. An additional 12–40 TWh of fuel could be cultivated in the form of coniferous mixed or deciduous forests on agricultural land that has either already been abandoned or is no longer needed (0.5–1.0 million hectares of fields and pasture land) (66). Field trials in Sweden indicate a higher sustainable biomass production rate (40–80 TWh/year) from this same land area (67, 68).<sup>25</sup>

The industrial cogeneration potential is a function of the need for process heat in industry. The heat need is in turn based on the introduction of heat-efficient processes. An estimate of the potential is provided in (69). We assume that half of this potential would be utilized by 2010, and that the systems used would have power-to-heat ratios of 0.7, based on steam-injected gas turbines. This will yield a potential electricity production of 3.5 TWh/year beyond today's level of 5 TWh.

## 3.4 The Supply Scenarios

To formulate various supply scenarios, it is necessary to adopt some decision rules governing the selection and ranking of electricity generation technologies and fuels. The key objectives are to minimize direct costs as well as non-economic factors such as emissions and energy-import dependency. To illustrate a range of possible outcomes, we construct three types of generation scenarios and apply them to the four demand scenarios developed above. In each scenario, we begin with an existing mix of 65 TWh hydro; 1 TWh each oil condensing and gas turbines; 5 TWh of industrial backpressure.<sup>26</sup> In the

<sup>25</sup> This corresponds to a productivity of 14.4 tons of dry matter per hectare per year.

<sup>26</sup> The hydro estimate includes approximately 2 TWh of additional output beyond the 1987 level. The remaining capacity in oil-condensing and gas turbine units (~25 TWh/year) is allocated to providing reliability reserves and is thus not included in these "typical-year" calculations. Because we dedicate these plants to this purpose, the construction of additional excess capacity is unnecessary to fulfill the reliability criterion. We construct our supply scenarios assuming no net power imports in a typical year.



Table 3. Generation scenarios: power and heat production, fuel use.

			Economic-Dispatch Scenario			
	Alpha (Power/Heat)	Busbar Cost (\$/kWh)	Reference Scenario	Efficiency Scenario	Hi-Eff. Scenario	Adv-Tech. Scenario
Existing Capacity (TWh <sub>e</sub> )						
Hydro		2.01	65.0	65.0	65.0	65.0
Combined heat & power (CHP)	0.5	4.94	6.5	6.5	6.5	6.5
Oil condensing power stations		5.85	1.0	1.0	1.0	1.0
Gas turbines		9.71	1.0	1.0	1.0	1.0
Industrial cogeneration (gas)	0.5	3.10	5.0	5.0	5.0	5.0
New Capacity (TWh <sub>e</sub> )						
Industrial cogeneration (biomass)	0.7	5.30	0.0	0.0	0.0	0.0
Fluidized bed/CHP (coal)	0.5	3.19	5.3	5.3	5.3	4.8
Steam-injected cycle CHP (gas)	1.1	3.19	5.3	5.3	5.3	4.8
Steam-injected cycle CHP (biomass)	1.1	5.60	0.0	0.0	0.0	0.0
Central station (coal)		4.17	25.2	10.9	3.4	0.0
Combined cycle (gas)		4.17	25.2	10.9	3.4	0.0
Wind generators		7.00	0.0	0.0	0.0	0.0
Total Electric Generation (TWh <sub>e</sub> )			139.5	110.9	95.9	88.0
Combined Heat and Power, Industrial Process Heat						
Industrial cogeneration (TWh <sub>th</sub> )			10.0	10.0	10.0	10.0
Municipal CHP (TWh <sub>th</sub> ) [includes 5 TWh RDF, etc.]			33.4	33.4	33.4	31.8
Supplemental district heating or process heat (TWh <sub>th</sub> )			9.6	9.6	9.6	11.2
Second-Order Fuel Use						
Fuel switching, to oil from electricity (TWh <sub>e</sub> )			-3.0	6.9	6.9	7.9
Fuel switching from electricity to natural gas in industry (TWh <sub>e</sub> )			0.0	2.1	3.6	3.6
Total Fuel Use (all energy services) (TWh)						
	Coal		96	60	41	31
	Oil		17	29	29	32
	Gas		86	55	42	33
	Biomass		0	0	0	0
	Total		199	144	112	96

Economic-Dispatch Scenario 6.5 TWh existing CHP is incorporated. In the other scenario existing CHP systems would be rebuilt/replaced using new technology with improved power-heat production ratios. This supply mix includes an excess production capacity of 20 TWh that is needed to insure the conventional planning criterion of 3% risk of energy shortage.

To the already existing generating capacity, we then add, in the specified order, additional capacity to satisfy the energy and power performance criteria. For cogeneration we assume that up to three-quarters of the municipal district heating needs are supplied through steam-injected gas turbines operated

Natural Gas/Biomass Scenario				Environmental-Dispatch Scenario			
Reference Scenario	Efficiency Scenario	Hi-Eff. Scenario	Adv-Tech. Scenario	Reference Scenario	Efficiency Scenario	Hi-Eff. Scenario	Adv-Tech. Scenario
65.0	65.0	65.0	65.0	65.0	65.0	65.0	65.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0
3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
18.3	18.3	4.4	0.0	5.0	5.0	0.0	0.0
13.0	13.0	13.0	9.5	26.3	26.3	17.4	9.5
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
29.7	1.1	0.0	0.0	29.7	1.1	0.0	0.0
3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0
139.5	110.9	95.9	88.0	139.5	110.9	95.9	88.0
15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0
33.4	33.4	20.8	13.6	33.4	33.4	20.8	13.6
4.6	4.6	17.2	24.4	4.6	4.6	17.2	24.4
-3.0	6.9	6.9	7.9	-3.0	6.9	6.9	7.9
0.0	2.1	3.6	3.6	0.0	2.1	3.6	3.6
0	0	0	0	0	0	0	0
4	17	31	31	4	17	11	12
124	60	32	23	96	32	23	23
50	50	50	50	90	90	84	68
178	127	113	104	190	139	118	103

in CHP mode. The amount of electricity cogenerated is determined by the system's annual average alpha value. When full heat output is not needed for district heating, the excess heat is used to raise steam which is injected into the gas turbine to enhance power production (70). The alpha value just cited refers to the ratio of total annual electricity produced to the total heat produced for district heating.

Detailed descriptions of the scenarios, economics, and emissions are shown in (71) and the generation mix for each scenario is shown in Table 3.



### 3.4.1 Economic-Dispatch Scenario

In order of increasing busbar cost, new power plants are constructed and used to meet the demand in excess of that provided by the existing plants. Here, the usage of the term Economic-Dispatch refers to long-term planning and is analogous to the short-term decision rule about which plants to operate. We assume a 50% coal, 50% natural gas generation mix. This is based on the assumption that market forces will cause natural gas prices to adjust until there is parity with the costs of gas-fired and between coal-fired electric power generation.

### 3.4.2 Natural Gas/Biomass Scenario

In this scenario, Sweden's existing *non-utilized* biomass resources (50 TWh fuel) are used to produce heat and electricity. The biomass is gasified and used first in steam-injected gas turbines to produce useful heat and electricity and then in district heating boilers if the electricity demand has been satisfied, and there are remaining biomass fuel resources. For industry, this includes 3.5 TWh of new biomass-fired cogeneration systems with alpha values of 0.7 as described by Larson *et al.* for steam-injected systems operating almost year-round at full heat output. We also include 3 TWh of wind-generated electricity to represent Vattenfall's estimate of the resource that might be exploited. Natural gas generation is then introduced according to economic dispatch, i.e., combined heat and power until the district heating demand is met and then conventional power stations.

### 3.4.3 Environmental-Dispatch Scenario

In this scenario, new power plants are constructed and used to meet the electricity and district heating demand in order of increasing CO<sub>2</sub> emissions. Biomass residues plus up to 40 TWh (fuel) production from "energy plantations" are utilized in combined heat and power stations, industrial cogeneration systems, and for district heating. Wind power is utilized as in the previous scenario (3 TWh). If needed, electricity and heat are then generated with natural gas according to economic dispatch.

## 4 Integrated Resource Planning

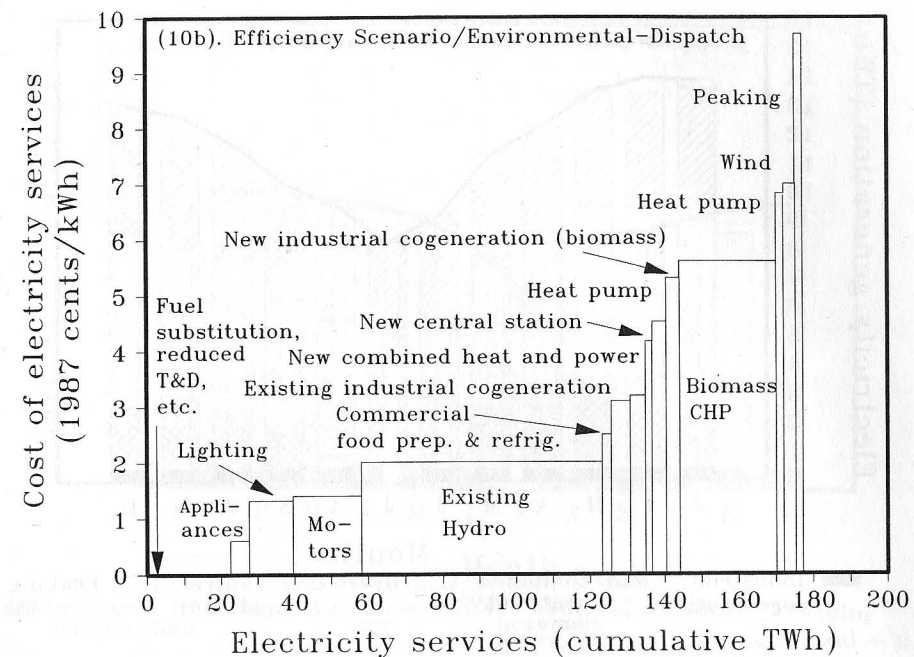
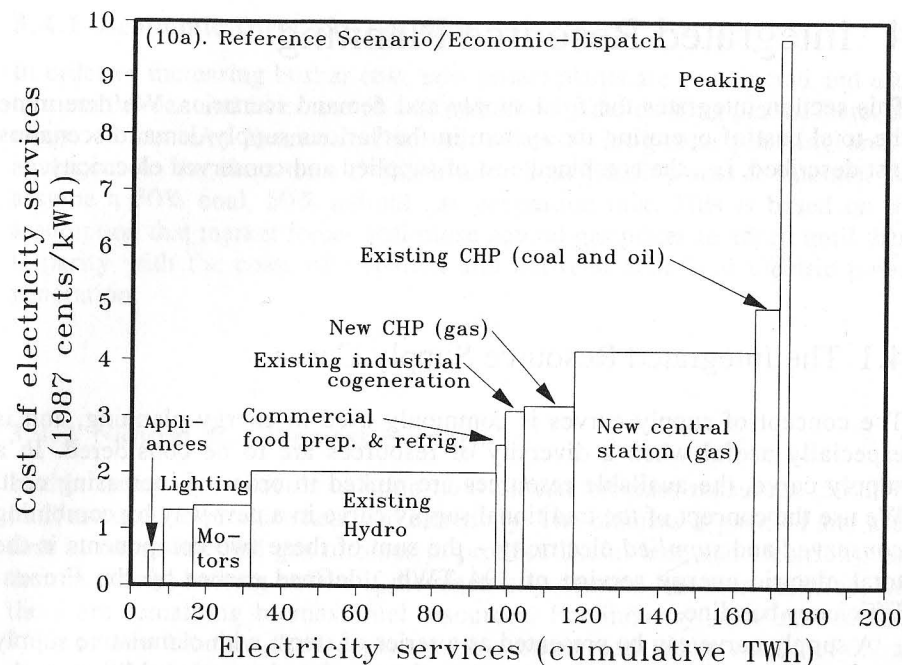
This section integrates the final supply and demand scenarios. We determine the total cost of operating the system in the various supply/demand scenarios just described, i.e., the combined cost of supplied and conserved electricity.

### 4.1 The Integrated Resource Supply Curve

The concept of supply curves is commonly used in energy planning, and is especially useful when a diversity of resources are to be considered. In a supply curve, the available resources are ranked in order of increasing cost. We use the concept of the traditional supply curve in a new way by combining *conserved* and *supplied* electricity – the sum of these two components is the total electric energy service of 194 TWh<sub>eq</sub> defined earlier by the Frozen-Efficiency baseline.

A supply curve can be presented as a series of steps, with cumulative supply on the horizontal axis and the incremental cost of each supply addition on the vertical axis. For supply-side resources, the y-axis value is the levelized busbar cost (cents/kWh) and for demand-side resources it is the cost of conserved electricity (also cents/kWh). We developed supply curves that combine these two kinds of resources, based on a ranking of their costs.

Twelve different supply curves could be drawn for various combinations of the four supply scenarios and three generation scenarios presented in this chapter. Each would supply 194 TWh<sub>eq</sub> of electricity services, but would do so with varying mixes of efficiency measures and types of power plants. Two such "integrated supply curves" are shown in Figures 10a and 10b. The first figure represents the Reference Scenario for demand and the Economic-Dispatch Scenario for supply, and the second figure shows the Efficiency Scenario and the Environmental-Dispatch Scenario. (Note that the supply curve is used here to rank and compare changes in electricity use resulting from some sort of capital investment. Therefore, the costs of fuels that replace electricity are included below instead of in the supply curves.) Sweden's district heating and industrial backpressure heat needs are also met in the scenarios but are not shown explicitly in the curves.



Figures 10a and 10b. "Integrated" electricity resource supply curves for Sweden. The curves rank scenario end-use technologies and new supply technologies (described in the chapter) according to their levelized per-kWh costs (6% real discount rate). The x-axis measures cumulative electricity conserved or supplied by 2010 with respect to the Frozen-Efficiency baseline and the y-axis measures the levelized cost for each technology. Fuel-switching is shown at zero cost because this is electricity use in buildings with existing multi-fuel systems that have an operating cost reduction at essentially no capital cost. The operating costs for fuel are counted in the section on total societal economics. The supply curves shown exclude efficiency savings for which we have not determined the investment cost (see the last footnote in Table 2).

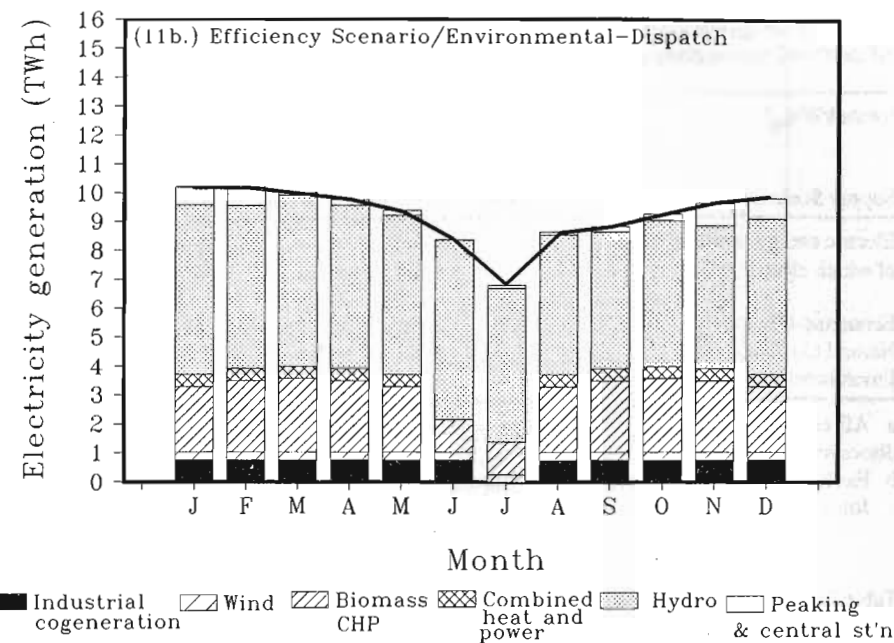
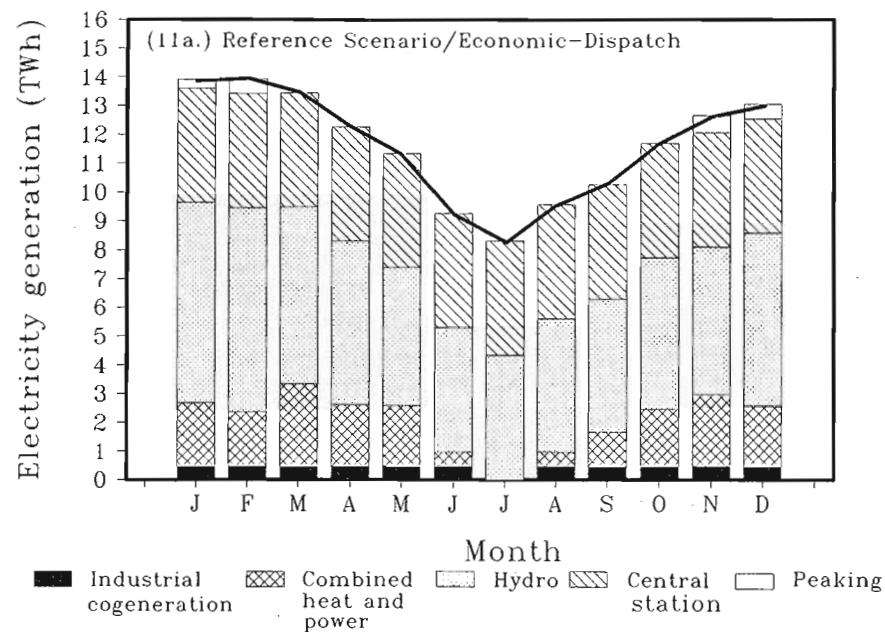
To present another aspect of the results, in Figures 11a and 11b we show the monthly electricity demand for the same supply/demand scenario combinations shown in the previous two figures.<sup>27</sup> In Figure 11b, electricity is supplied mostly with domestic resources. The decreased seasonality of demand is also

notable, mainly due to the assumed switching from electricity to fuel, primarily oil, for space heating. Hydro capacity is utilized differently in the two scenarios, in order to operate the CHP systems efficiently.

## 4.2 Scenario economics

Many types of economic costs are included within the system boundary that we have defined for the scenarios. We have tabulated the annualized costs of existing electricity capacity, new electricity capacity, district heating, natural gas transmission, fuels used in switching away from electric space heating and electric-based process heating in industry, and the investments in improved efficiency. Focusing first on electric energy services, we can define the total cost of these services as the annual investment in generating capacity, efficient

<sup>27</sup> We have apportioned the weather-independent consumption for our scenarios evenly across the months, except for industrial use in July which we reduce to 67% of the annual average, due to the month-long national holiday (72).



Figures 11a and 11b. Monthly electricity generation and supply mix corresponding to two demand scenarios. Figure 11a shows the Reference Scenario demand level and the Economic-Dispatch supply mix. Figure 11b shows the Efficiency Scenario and the Environmental-Dispatch supply mix with 90 TWh of biomass fuel availability. The demand for lighting and space heating (including that in industry) is allocated to the months according to average-year heating degree-days in Stockholm. Water heating in one-fuel systems is spread evenly over the months. Because of the presence of time-of-use rates, electric water-heating in multi-fuel systems is assumed to occur in the six-month summer period of March-August. Based on historic statistics, industrial demand during the national holiday month (July) declines by 33%. Monthly hydro production in 2010 is based on Vattenfall's estimates for an average rainfall year. Power generation by cogeneration systems is curtailed during summer because of minimal need for district heating.

end-use technology, and fuel switching, divided by 194 TWh<sub>eq</sub> (Table 4). In every case, total costs tend to decline as efficiency increases. This is because the average cost of conserved electricity is lower than the average supply cost.<sup>28</sup>

<sup>28</sup> It has not been possible to identify the costs for all of the efficiency measures in the scenarios. In the Efficiency Scenario, the supply curve includes costs for 66 out of the 83 TWh efficiency improvement beyond 1987. There is no reason to believe that the remaining TWh are more or less costly but we assume that they will cost 50% more per kWh. In the High-Efficiency Scenario, we assume that the unmonetized electricity services cost 100% more per kWh. No estimate is made for the Advanced-Technology Scenario.

All of the energy services in our system (obtained by combining the costs of district heating and process heat with the results just discussed) amount to 247 TWh<sub>eq</sub> (194 + 53). The costs per kilowatt-hour equivalent of these energy services are comparable to today's busbar costs of electricity and district heating in Sweden, both about 2.8 cents/kWh. This busbar cost is, by definition, equal to the costs of electricity services in 1987. The annualized societal costs are summarized in Figure 12. The costs lie between \$5.5 and \$7.0 billion per year (2.2-2.8 cents/kWh<sub>eq</sub>) over the full range of supply and demand scenarios.

The average cost of the new electricity supply would range from 3.2 cents/kWh to 5.8 cents/kWh<sub>e</sub> (including wind) (Table 5). The marginal cost would be up to 5.6 cents/kWh, when biomass is the marginal resource.

We tested the sensitivity of the results shown in Table 4 to alternate assumptions about the cost of conservation:

- (i) By increasing the cost of conserved electricity by 50%, the cost of electric energy services for the High-Efficiency/Environmental-Dispatch Scenario rises from 2.3 to 2.7 cents/kWh<sub>eq</sub>, still less than the 1987 value of 2.8 cents/kWh<sub>eq</sub>.
- (ii) The Reference Scenario/Economic-Dispatch result rises from 2.6 cents/kWh<sub>eq</sub> to 2.8 cents/kWh<sub>eq</sub> given the same assumption.

Table 4. Total annualized costs for all 194 TWh<sub>eq</sub> electric energy services (generating capacity, efficient end-use technology, and fuel switching).<sup>a</sup>

(cents/kWh <sub>eq</sub> )		Demand Scenario			
		Reference Scenario	Efficiency Scenario	High-Efficiency Scenario	Advanced-Technology Scenario
Supply Scenario	1987				
Electric energy services (TWh <sub>eq</sub> ) <sup>b</sup>	194	194	194	194	194
of which electricity supply (TWh <sub>e</sub> )	129	140	111	96	88
Economic-Dispatch	2.8 <sup>c</sup>	2.6	2.3	2.1	---
Natural Gas/Biomass		2.7	2.4	2.3	---
Environmental-Dispatch		2.9	2.6	2.3	---

a All costs for supply and demand-side investments are calculated using the same 6% real discount rate.

b Excludes 53 TWh of process heat and district heating in each case.

c Joint Council of the Swedish Electric Power Producers (Kraftsam) estimate.

Table 5. Average cost of new capacity.

(cents/kWh <sub>e</sub> )		Demand Scenario			
		Reference Scenario	Efficiency Scenario	High-Efficiency Scenario	Advanced-Technology Scenario
Supply Scenario					
Electricity Generation (TWh <sub>e</sub> ) <sup>a</sup>	68	39	24	15	
Economic-Dispatch	4.0	3.8	3.6	3.2	
Natural Gas/Biomass	4.4	4.5	5.3	5.8	
Environmental-Dispatch	4.8	5.3	5.7	5.8	

<sup>a</sup> In the Economic-Dispatch Scenario, new capacity construction is 6.5 TWh lower because existing CHP plants are utilized rather than reconstructing new, more-efficient plants.

We also tested the impact of 50% higher biomass fuel costs. This would result in biomass-STIG busbar costs of 7.6 cents/kWh, up from the base case value of 5.6 cents/kWh:

- (i) For the Environmental-Dispatch Scenario, the total electricity service costs for the Reference Scenario and High-Efficiency Scenario demand levels were 3.2 cents/kWh and 2.6 cents/kWh, respectively, up from the base case values of 2.9 cents/kWh and 2.3 cents/kWh.

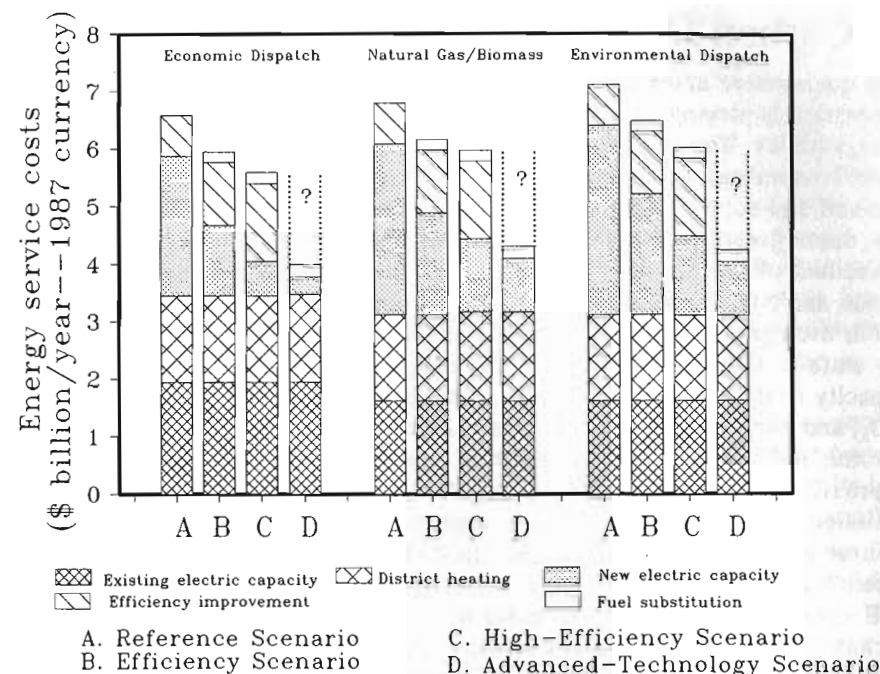


Figure 12. Energy service costs in 2010. The total annualized costs for 247 TWh<sub>eq</sub> energy services today provided by direct electricity production, combined heat and power, industrial cogeneration, efficiency investments, and the costs of substitute fuels are included in the diagram. No conservation investment has been estimated for the Advanced-Technology Scenario. The values for existing capacity vary in some cases because some existing CHP capacity and industrial backpressure are replaced with biomass-fired generators in those scenarios. Costs are based on constant real fuel prices shown in Box 1.

- (ii) For the Reference/Environmental-Dispatch Scenario, the average cost for new electricity supply will rise from 4.9 to 5.8 cents/kWh<sub>e</sub>. For High-Efficiency/Environmental-Dispatch, the cost will rise from 5.7 to 7.5 cents/kWh<sub>e</sub>.

Even given these assumptions, the fact remains that costs for electricity services in the Efficiency scenarios are lower than in the Reference scenario, as does, of course, the higher costs of biomass-using scenarios in relation to fossil-fuel-only scenarios.



## 5 Carbon Dioxide and Other Emissions

The quantitative assessment of the emissions associated with power and heat generation is playing an increasingly large role in energy systems analysis and energy policy. The most ominous manifestation of energy-related emissions is global warming, commonly known as the "greenhouse effect". For each demand and supply scenario, we have assessed the output of carbon dioxide, the main greenhouse gas.<sup>29</sup> In addition, we have tabulated the airborne emissions of certain heavy metals (cadmium and mercury), hydrocarbons, sulfur, and NO<sub>x</sub>, plus solid waste materials (e.g., ash) left behind.

For each generation mix in the supply scenarios, we apply emissions factors for state-of-the art combustion technologies (73, 74). All new generating capacity in the scenarios complies with Sweden's 1995 guidelines for sulfur, NO<sub>x</sub>, and particulates emissions (75).<sup>30</sup> In the Economic-Dispatch Scenario, we assume today's fuel mix in existing central heat and power production: approximately 70% coal, 30% heavy fuel oil. For the purpose of estimating emissions from the district heating sector and from industrial process heat, we assume a fuel conversion efficiency of 85% and exclusive use of natural gas, where biomass is not used.

Because each efficiency scenario incorporates some fuel substitution, we include the associated emissions from this increase in fuel use. Most of the effect is due to conversions from electricity to heating oil (6.9 TWh<sub>e</sub>) and the replacement (upon retirement) of large-scale heat pumps with fuel-based district heating systems (2 TWh<sub>e</sub>), but there is also increased natural gas use in the steel industry that displaces electricity now used in electric arc furnaces and other process heating tasks (~4 TWh<sub>e</sub>).<sup>31</sup> In order not to underestimate the CO<sub>2</sub> effects, we assume that all conversions from electric space heating are to oil (while in reality some will likely be to wood fuel, which makes no net CO<sub>2</sub> additions to the atmosphere, or to natural gas). The Reference Scenario

<sup>29</sup> Other important greenhouse gases are methane, CFC-11, CFC-12, nitrous oxide, and tropospheric ozone. Carbon dioxide is thought to be responsible for about 50% of the warming effect.

<sup>30</sup> The 1995 emissions guidelines for power production facilities are: sulfur (0.05 g S/MJ fuel burned), NO<sub>x</sub> (0.05–0.10 g NO<sub>x</sub>/MJ, units over 300 MW<sub>e</sub>) and 0.10–0.20 (g NO<sub>x</sub>/MJ, units below 300 MW<sub>e</sub>), particulates (20 mg/MJ, annual average for coal-based systems).

<sup>31</sup> We select a Plasmascrap process based on natural gas. Plasmascrap can also use 45 kg coal per ton of steel produced (76). To put this prospective emissions increase in perspective, if SSAB's use of coal (650 kg/ton) remains the same in 2010 and their production grows from 3 Mtons/year to 3.6 Mtons/year, then coal use will be 2,340 kilotons annually. Given Vattenfall's assumed production trends, steel output from electric arc furnaces would grow from 1.6 Mton/year to 1.9 Mtons/year. The corresponding incremental coal requirement in 2010 is 86 kilotons (at 45 kg/ton).

includes some switching from fuel to electricity, and we credit this to lower emissions from oil-fired heating systems.

As mentioned earlier, a present national goal is to freeze current CO<sub>2</sub> emissions. The current levels from the power and heat sector are low due to an electricity production mix that is based almost entirely on nuclear and hydroelectric power. Were there interest in constructing fossil-fuel-based power plants, the option always exists to seek offsets outside the power and heat sector, but this strategy may be unacceptable in the long run. Natural gas might be allowed as a transitional fuel if carbon dioxide emissions can be correspondingly reduced in other sectors. The same holds for other fossil fuels, although the reduction of CO<sub>2</sub> emissions in other sectors would then have to be larger because of the higher amounts of CO<sub>2</sub> released when using these other fuels.

In Figures 13a-13d the carbon emissions from the heat and power sector (247 TWh<sub>eq</sub>) are shown for each generation and demand scenario. The curves show the total annual costs of providing the energy services. The results for carbon reveal an extremely broad range of emissions and yet very similar costs, regardless of the generation mix. The set of bars accompanying the Economic-Dispatch Scenario show that efficiency will indeed reduce carbon, but not nearly enough to meet the target. On the other hand, the Environmental-Dispatch Scenario may not suffice either. A combination of substantial efficiency improvement *and* low-carbon generation technologies is the only solution among the twelve combinations shown. And, as shown in Figure 13, the total societal economic costs of the high-CO<sub>2</sub> scenarios may be *higher* than the costs of the low-CO<sub>2</sub> scenarios.

As shown in Table 6, only three of the twelve scenario combinations result in per-capita carbon emissions – including those emissions outside of the power and heat sector – equal to or lower than those in 1986.<sup>32</sup> However, even the best case is nearly two times the world average of ~1 ton/capita annually (79).

In the highest emissions case, total carbon emissions increase to over 150% of their 1986 levels and those from the heat and power sector alone increase to ~500%. In contrast, the High-Efficiency/Environmental-Dispatch case results in a 10% reduction in CO<sub>2</sub> from today's levels. Emissions from the power and heat sector alone decline by 35% from today's levels (Table 7). In 1986, the power and heat sectors accounted for 15% of Sweden's CO<sub>2</sub> emissions whereas – assuming constant emissions from other sectors – in 2010 with coal/gas economic dispatch and efficiency improvements corresponding to the Reference Scenario, it would be the source of 50% of national emissions.

<sup>32</sup> In calculating Sweden's total CO<sub>2</sub> emissions, we include the energy-related uses of coal, oil, and gas from (78).

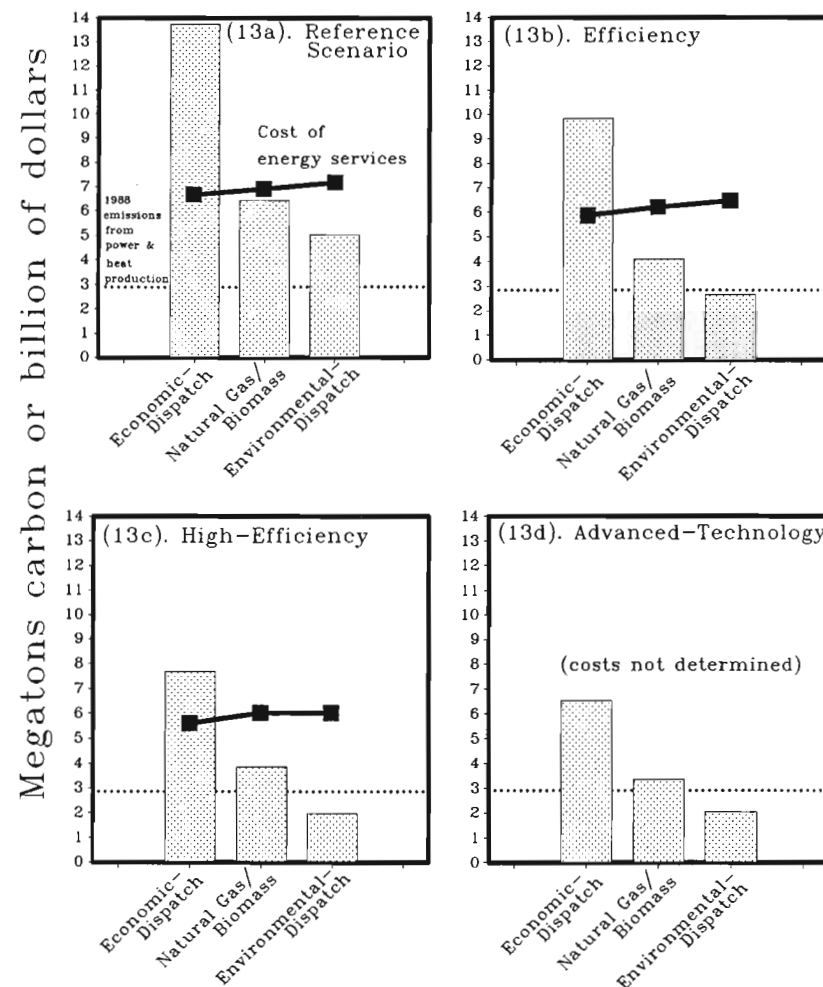


Figure 13a-13d. Annual carbon emissions from the production of heat and power within the system boundary, plus the use of substitute fuels in 2010. Results are shown for each generation scenario and demand scenario. The total costs of energy services from Figure 12 are given by the curves.

No CO<sub>2</sub> emissions from the transportation of fuels are included. For domestic biomass they will be very small, but this is not necessarily the case for the import of coal.

We calculated the offsets required for each scenario if carbon emissions from the power and heat sector are to remain at their present levels. In all but

Table 6. Per-capita carbon emissions (all sectors)<sup>a</sup>.

Supply Scenario	(tons/capita-year)	Demand Scenario			
		Reference Scenario	Efficiency Scenario	High-Efficiency Scenario	Advanced-Technology Scenario
Economic-Dispatch	1.91	3.10	2.67	2.40	2.27
Natural Gas/Biomass		2.26	1.99	1.96	1.89
Environmental-Dispatch		2.10	1.83	1.73	1.74 <sup>b</sup>

a Assumes constant 1986 levels from outside the power and heat sector. The global average emissions were 1.03 tons/capita-year in 1986. For derivation, see Bodlund *et al* (77).

b Results are higher than in the High-Efficiency Scenario due to greater amounts of fuel switching.

Table 7. Carbon emissions in 2010 (power and heat sector).

Supply Scenario	(Mtons/year)	Demand Scenario			
		Reference Scenario	Efficiency Scenario	High-Efficiency Scenario	Advanced-Technology Scenario
Economic-Dispatch	2.9	13.6	9.9	7.6	6.5
Natural Gas/Biomass		6.4	4.1	3.8	3.3
Environmental-Dispatch		5.0	2.7	1.9	2.0

three of the twelve cases, substantial offsets would be necessary. For reference, total 1986 carbon emissions from industry were approximately 4.2 Mtons/year; from residential space heating 3.8 Mtons/year, and from road transport 4.7 Mtons/year. Based on the emissions shown in Figure 13, achieving the highest offset of ~10.5 Mtons/year does not seem conceivably possible. Attaining full offsets in any of the Economic Dispatch cases would be quite difficult, as it would for the Reference Scenario demand for any of the three generation strategies. Substantial improvements in automobile efficiency and additional efforts to conserve heating oil in the buildings sector could in principle achieve sufficient offsets for some cases where the natural gas/biomass systems are used. However, it must be kept in mind that these offsets may be needed to meet future agreements, such as those outlined in the recent Toronto and Hamburg recommendations that call for 20%-50% reductions in CO<sub>2</sub> emissions by 2005 and 2015, respectively (80, 81).

Another alternative – the control of CO<sub>2</sub> emissions from fossil-fueled power plants – has been proposed, but in coal plants it is estimated that 16% of the power plant's capacity would be required to operate the control system and



overall production costs would increase by 56% to 100%. The capital investment would range from 70% to 150% of the existing capital investment (82).

Some additional carbon reductions will occur over the short run if biomass plantations are used. These plant materials will absorb carbon from the atmosphere for as many years as the size or intensity of plantation area is being increased. We have not included this "biomass buffering" effect in our analysis.

We also evaluated other emissions. Figures 14a and 14b present a comparison of carbon dioxide and other emissions by showing an index for each by-product for each demand level, where 100 equals the Reference Scenario/Economic-Dispatch combination. In the fossil-based Economic-Dispatch generation scenario, nitrogen oxides, polyaromatic hydrocarbons, and heavy metals (cadmium and mercury) are approximately 40-70% lower in the Efficiency scenarios than in the Reference case. Cadmium levels are only slightly lower in the Environmental-Dispatch Scenario because those in coal are replaced by those in biomass. There is an important difference, however, in that coal mining mobilizes heavy metals otherwise bound in mineral form (and the greenhouse gas methane), thereby increasing the amount of heavy metals circulating in the bio-geological system.

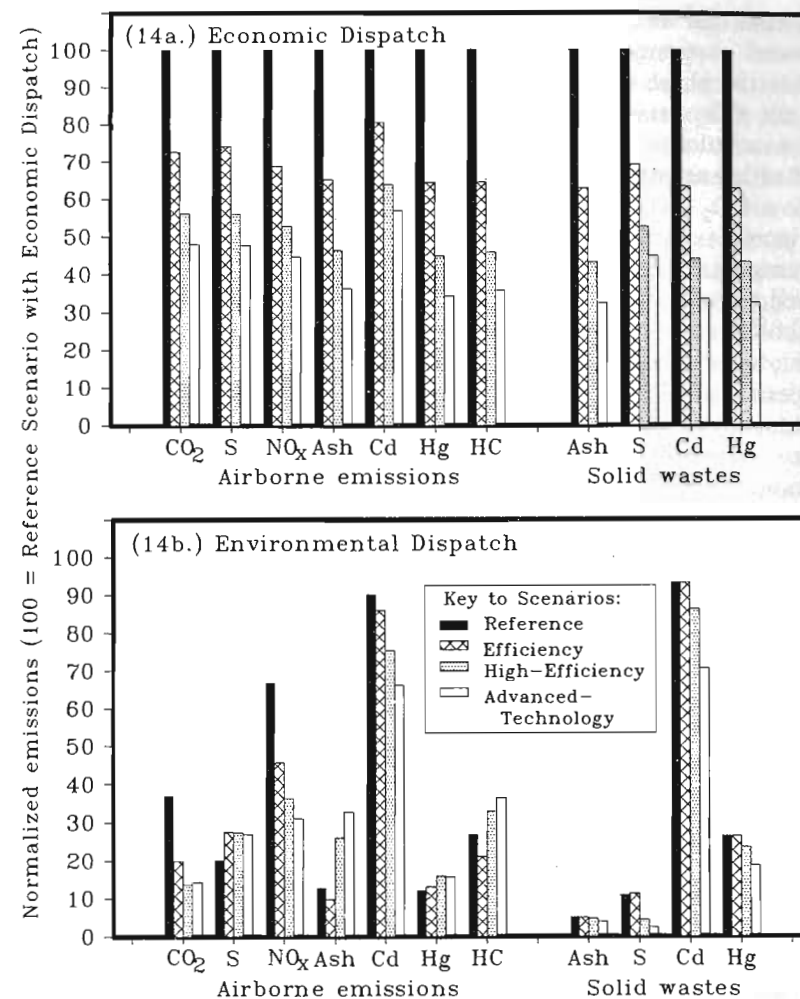
For all pollutants, emissions will vary between years, primarily depending on the annual hydro-power production. Seen as an average over many years, the emissions presented here would be largely representative, but we have not made a detailed analysis of this.

Before concluding, we note that it is important to guard against adverse environmental effects that might result based on the assumptions of the scenarios. For example, it would be necessary to make use of environmentally acceptable ways of growing the biomass beyond that already available as waste products, improving buildings, designing gas turbine exhaust cleaning systems, avoiding CFCs and other greenhouse gases in all applications. The strategy described in this chapter is not in conflict with these guidelines. Concerning CFCs from heat pumps, we assume successful development of benign alternatives (see the chapter by Berntsson (83) in this volume).

## 6 Policy Implications

### 6.1 The Challenge of Choices

The preceding scenarios illustrate some of the choices available to Sweden in determining her electricity future. It is possible from a technical standpoint to



Figures 14a and 14b. Emissions indices. The height of the bars is shown as an index. In this way, the relative changes for many different materials can be easily compared. The following waste product data are for the Reference Scenario/Economic-Dispatch Scenario case, i.e., the one indexed to equal 100 in Figure 14a. They can thus be used to directly estimate the corresponding values for the other bars, according to their respective indices. *Annual Airborne Emissions*: net carbon emissions 13,644 ktons [C]; sulfur emissions 19 ktons [S]; NO<sub>x</sub> emissions 89 ktons NO<sub>x</sub>; airborne ash 6 ktons; cadmium emissions 52 kg [Cd]; mercury emissions 278 kg [Hg]; Polyaromatic hydrocarbon emissions 390 kg; *Annual Solid Waste Production*: ash waste material 1,720 ktons; sulfur waste material 105 ktons [S]; cadmium waste material 3,459 kg [Cd]; mercury waste material 1,106 kg [Hg]. (note; NO<sub>x</sub> emissions are computed here as their NO<sub>2</sub> equivalents.)

find paths that satisfy the demand for electricity services associated with continued economic growth, uphold environmental quality standards, and expedite the phase out of nuclear power as planned. The scenarios have very different CO<sub>2</sub> emissions, while other environmental aspects meet present environmental standards. These low-CO<sub>2</sub> scenarios would require the increased use of efficient end-use technology in all sectors as well as the installation of new low-CO<sub>2</sub> generating facilities. Use of coal and natural gas would lead to large increases in CO<sub>2</sub> emissions compared with present levels. The economic differences are much smaller. In fact, the costs of the Efficiency and High-Efficiency/Environmental Dispatch scenarios would be similar to or lower than those for the Reference/Economic Dispatch scenario, as calculated in this chapter, based on today's knowledge about costs and prices.

Experience suggests that such a development would not happen by itself. Individual decision-makers tend to optimize for themselves rather than for society at-large. By definition, the Reference Scenario illustrates the development that one could expect under present operation of the marketplace. The difference between the Reference Scenario and the High-Efficiency Scenario – 44 TWh/year – can be thought of as one measure of the opportunities for alternative market dynamics. To capture some or all of these savings, policies would have to be shaped to make markets work better and stimulate actors in all sectors to make use of the technical opportunities we have described in the preceding pages. Information, education and training, rules, and regulations would have to reflect this by making the national good also be the actor's good.

The chapters by Geller (84), Williams (85), and de la Moriniere (86) describe how such policies might be designed, markets organized, and the necessary financing arranged, and the chapter by Geller *et al* (87) describes the potential for research and development to help accelerate the introduction of new technologies into the marketplace. These four chapters discuss many policy options, and the experiences that are available from testing some of them in the U.S. and in France.

It is evident that electricity prices are only one of several significant factors in the process of achieving a cost-effective total development of the energy system, or the electricity system, and that there is great uncertainty in price/demand relationships (88).<sup>33</sup> Electricity costs are often not very significant and consumers lack influence over how the equipment they purchase is designed. It is therefore not surprising to find that the effective

rates-of-return demanded by consumers are often 50–100% or higher (89, 90), much above the interest rates commonly used in evaluating supply investment options. This suggests that the total system will not develop in a least-cost direction. Reflecting long-run marginal costs in rate structures (e.g., in inverted-block tariffs that convey the marginal cost incentive without increasing the total cost of electricity) is probably necessary but not sufficient to bring the options discussed in this book into reality.

Policy measures would also have to be formulated on the supply side, because costs of new generating capacity are higher than average generating costs. This is due to the large, low-cost hydropower production in Sweden. The average costs of new supplies would range up to 5.8 cents/kWh<sub>e</sub>, well above the new system-wide average cost of ~3 cents/kWh<sub>e</sub>. The problem is most pronounced in the High-Efficiency/Environmental Dispatch scenario. The extent of policies required to stimulate new generation under these circumstances depend on electricity pricing principles. With marginal cost pricing, costs would be covered, but otherwise one could not expect non-hydro-owning utilities or industries to invest in, e.g., cogeneration. An arrangement where central utilities purchase power from independent power producers on an avoided-cost basis would be one way to approach this dilemma.

As discussed in other chapters in this book, research and development work remain to be done on many complex issues related to some technologies included in the scenarios. This work should be done now, and not postponed, if these technologies are to contribute significantly by 2010.

## 6.2 Lead Times

A perceived dilemma in selecting the end-use efficiency improvements as a major component of an overall electricity strategy is the lack of data on the effectiveness of various policy mechanisms intended to secure these resources. Can power supply planning that fulfills the usual reliability criteria be accomplished without investing so much in supply capacity that the economic imperative to utilize this excess capacity becomes an obstacle for continued efficiency improvement?

The answer to this question lies partly in the fact that the new supply technologies have short lead times, as compared with traditional central-station generating facilities. Both combined cycles and the advanced gas turbines (described by Williams & Larson in this volume) would require about 3 years for construction and 2 years for licensing, assuming fuel supplies such as

<sup>33</sup> For a discussion of electricity price responsiveness in Sweden, see Mills, E. 1988. *The role of energy prices in shaping electricity end-use structure and demand in Sweden*. Manuscript in preparation. Lund University. Department of Environmental and Energy Systems Studies. Report to Vattenfall's Uppdrag 2000 project.

natural gas and biomass are available on the market in the relatively small quantities that would be needed for each additional unit. Coal and oil are readily available and can by and large be transported the point of use with the existing infrastructure. Natural gas would require a transmission system, and biomass is presently available only at the levels specified in the Natural Gas/Biomass Scenario. A large natural gas transmission system would require 5–10 years to build. To implement the Environmental-Dispatch scenario would involve a 5- to 7-year lead time for energy plantations. For both natural gas and biomass, time is needed to establish a market.

To the extent that electricity plans utilize short-leadtime strategies, the traditional problem facing utilities having to forecast electricity demand 8 or 10 years into the future – and increase the generating capacity sufficiently to mitigate the forecasting uncertainties – can be reduced. It thus becomes possible to follow load growth and the effectiveness of efficiency-improvement policies, and to respond to the realities as they develop, while maintaining the traditionally high reliability standards, but with far lower uncertainty (and thus expense) than has been the case historically.

Although all scenarios have abundant excess capacity, the use of steam-injected gas turbines offers an additional route to winter-time extra reserve power production capacity. If heat normally supplied in cogeneration using these units is shifted to the stand-by oil-fired boilers needed for backup in every district heating system for reliability reasons, this frees up steam that can augment power production. In this way, reserve boilers contribute to an improved reserve margin in the power system.

*Demand-side* opportunities can be utilized at the rate of capital turnover and expansion. This often means 10–20 years for full penetration. Fuel switching, on the other hand, can be much faster (a property that is disadvantageous if the switching is reversed at a later date).

When utilizing demand-side resources, it becomes necessary to account for the lead time involved with programs or other mechanisms intended to accelerate the introduction of end-use technologies. For scenarios that rely on commercially available technologies, a key component is the speed with which a given program can achieve a targeted participation rate. For scenarios that rely on technologies still under development, the key factor is the rate at which research and development proceed and thus bring new technologies to marketplace.

In any case, developing demand-side resources begins with identifying them. This chapter has provided an assessment that could be expanded upon. Vattenfall has initiated a market-research project called “Uppdrag 2000” to identify the cost-effective conservation opportunities in Sweden (91). Over the next few years, the project will spend \$60 million and have a staff of roughly 70 people. The work will focus mostly on demonstration projects intended to obtain actual data on technical and behavioral issues in each sector. There

remains a three- to four-year period of continued investigations before implementation begins.

### 6.3 Balance of Payments

Some of the preceding scenarios would improve the balance of payment situation in Sweden. In recent years, Sweden's balance of payments has oscillated from year to year between net debts and net credits with an annual balance of plus-or-minus \$1 billion/year between 1983 and 1986 (92). The size of the impact for the scenarios would be primarily a function of the difference between the cost of no-longer imported uranium and newly-imported coal, gas, and/or oil. We find that for a demand level corresponding to the Reference Scenario, and a fossil-based supply mix, that the impact on balance of payments would be adverse whereas the two Efficiency plus Environmental-Dispatch scenarios indicate strong benefits.<sup>34</sup> At one extreme (Reference/Economic-Dispatch) the costs of imported coal for power generation and of oil for district heating would be \$1.4 billion/year. At the other extreme (High-Efficiency/Environmental-Dispatch) the cost of imports would be \$0.25 billion/year.

The cost of electricity services, especially to industry, is an important component of competitiveness and the balance of the payments equation. The closure of some industrial firms in the Reference Scenario is intended to reflect their sensitivity to the cost of electricity. In Table 4 we saw that for several of the scenarios, the costs of producing electricity services were comparable to or lower than today's.

<sup>34</sup> Imported uranium today costs \$425 million/year, based on Vattenfall's estimate of 0.652 cents/kWh for uranium fuel in 1987 and 65 TWh of nuclear-based generation. Let us consider two simplified cases. At one extreme, the fossil fuel imports required to generate 74 TWh/year (the difference between the Reference Scenario demand and projected hydroelectric production) would be \$1,600 million at 0.86 cents/kWh (fuel) coal import price and 40% conversion efficiency in the power plant. Thus, an adverse impact on the balance of payments would result. At the other extreme, in a low-demand scenario with biomass fuel (but accounting for 15 TWh fuel switching to imported oil at \$20/bbl), the cost of fossil fuels would be only \$250 million. In addition, were district heating to be provided from biomass fuel, oil imports could be further reduced by approximately \$950 million. We have not estimated the effects of new power plant construction and conservation-related capital investment, but most of these things can be produced in Sweden. It is clear that efficiency and a domestic-based fuel mix could have a significant positive impact on Sweden's balance of payments in the future.

## 7 Summary and Conclusions

We have presented four electricity demand scenarios for Sweden in the year 2010, based on different levels of electricity end-use efficiency. We combined the results with three generation scenarios, based on the utilization of various fuels and generation technologies. All of the scenarios assume 1.9% annual growth in gross domestic product and the corresponding amount of new buildings construction, industrial output, appliances purchased by households, etc. Each scenario combination provides all the energy services associated with this economic growth. Based on the final demand levels and supply mixes, we evaluated the total costs of energy services and the associated emissions of carbon dioxide and other by-products of heat and power generation. We did not evaluate the impact of higher or lower GDP trends nor we did we test the implications of different lifestyle developments.

There is a conceptual difference between some of the demand scenarios. The Reference Scenario is based on expectations of market behavior in the absence of new policy measures but with a 50% increase in real electricity prices. This scenario also assumes some price-induced industrial plant closures in the steel and electrolysis subsectors. Two other scenarios illustrate the results of more intensive use of electricity-efficient end-use technologies. These technologies are cost-effective in comparison with new electricity generation, based on a 6% real discount rate, and no direct taxes. In the last scenario, "Advanced-Technology", we assume the use of technologies still under development.

In the scenarios, direct use of electricity contributes between 88 and 140 TWh of Sweden's 194 TWh equivalent demand for electric energy services in 2010. The reductions in electricity use are brought about largely by improvements in lighting, motors, miscellaneous office equipment, and (except in the Reference Scenario) substitution of electric space heating by fuel. The additional oil use from fuel conversions is equivalent to 4% of Sweden's total oil imports in 1987 (based on replacing 6.9 TWh of electricity).

All the scenarios satisfy present environmental guidelines, but, obviously, some of these scenarios do not meet the environmental ambition of keeping CO<sub>2</sub> emissions constant. Given presently known technologies, we find that to achieve the economic growth mentioned above, fulfill national ambitions of keeping CO<sub>2</sub> emissions at or below their present level, and provide energy services requires a *combination* of energy-efficiency and low-carbon electricity supply strategies. Depending only on one or the other will not suffice.

In order to keep carbon emissions at or below the present level, bio-fuels have to be used to avoid the five-fold increase in carbon emissions from the power and heat sector that would result from using natural gas and coal to meet a demand level of 140 TWh. Furthermore, with two of the low-electricity scenarios, Sweden could provide a large fraction of its heat and

power with domestic resources. A prerequisite for using bio-fuels in this way is completion of biomass gasification technology development.

These Efficiency scenarios could be attained by 2010 at an overall cost of electricity services of 2.6 cents/kWh<sub>eq</sub> or less, versus a busbar cost of 2.8 cents/kWh in 1987, and a marginal cost of 4.2 to 5.6 cents/kWh<sub>e</sub> (depending on whether natural gas or biomass is the marginal resource), including all investment in end-use technologies. On the supply side, the use of biomass is more expensive than that of natural gas or coal, and this extra cost can be seen as a price for reducing CO<sub>2</sub> emissions. On the other hand, we have chosen measures on the demand side that reduce all emissions (including CO<sub>2</sub>) and deliver the electricity services at a cost *less than* that of constructing and operating fossil fuel power plants.

In evaluating the economic costs and considering the uncertainties, we are reluctant to say that either scenario is more expensive than the others in supplying all the energy services within the system we study. However, we submit that the societal costs per unit of energy services in the Efficiency scenarios do not increase from their current levels and CO<sub>2</sub> emissions are 35% lower in two cases.

Because the development of the preceding scenarios is based on a national perspective, the associated benefits would not necessarily be attractive to individual actors. These actors may or may not find it in their interest to pursue the technical opportunities that comprise the scenarios, e.g. industrial cogeneration and biomass recovery. To deal with this, policies will have to be shaped to bring individual actors' interests in line with the national interest. Some policy mechanisms could be implemented by the Swedish utilities as they become full energy service companies in the sense that Edison intended, but many other entities also have key roles to play.

From the point of view of a utility, a new type of uncertainty enters the supply planning process because future demand-side policies and their impacts are hard to predict. Whereas U.S. utilities and local governments have gained considerable experience with demand-side planning – thereby reducing the associated planning uncertainties – there is a great lack of experience in the Swedish context. Also, many of these policies would have to be formulated and implemented by non-utility actors, while the utilities would retain responsibility for providing the required electricity.

\* \* \* \*

The problems and opportunities we have described here are not unique to Sweden. Bringing down primary energy use by increasing end-use efficiency is the key strategy to deliver society's desired energy services and at the same time contribute to the amelioration of major global problems (93). The

efficient use of energy illustrated in the scenarios would enable Sweden to develop her energy system in ways compatible with solving global problems.

As the twenty-first century approaches, the Swedish society is planning for an expanding use of services from electricity and energy. The great business opportunity for utilities and entrepreneurs is to make the electric energy services their business activity. This will be an exciting era, with a key role for high-technology in both the supply and demand arenas. The new challenges are in policy-making and in the marketplace.

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## Notes to Box 2

<sup>a</sup> The percentages exclude changes in saturation, i.e., they are calculated based on the change in the electricity consumption per appliance. Appliance savings shown here are weighted by the use in single- versus multi-family homes. The appliance intensities are from Vattenfall and Nørgård (8). Nørgård's per-appliance estimates for freezers and combination refrigerator/freezers are adjusted upwards by 26% (single-family) and 11% (multi-family) to account for the anticipated increase in use of automatic defrost.

<sup>b</sup> For the residential sector, we consider the replacement of existing incandescent lamps with compact fluorescent lamps using McGowan's technology estimates (9). Penetration is based on Vattenfall's assumptions about the number of lamps that can be replaced (only 5 out of 23 lamps per house) due to limiting factors such as frequent cycling. The Vattenfall model assumes substantial "takeback" of savings as customers increase lighting on-time by about 30%. [This is assumed to occur because information supplied with the lamps instructs the users to operate them for 4 hours at a time.] In the last two Scenarios, we assume that most of the incandescent lamps not converted to compact fluorescent lamps are instead replaced with new, efficient incandescents (20% savings). For the services sector, we assume that 30% of current lighting energy use (i.e., a much lower percentage of the lamps) is by incandescent lamps and that

compact fluorescent replacements are applicable; 5% are flood and area lighting suitable for IRF and metal-halide lamps; and 65% are fluorescent fixtures suitable for some mixture of electronic ballast retrofits, occupancy and daylighting sensors, and better lamps. Thus, the savings shown in the Box are weighted averages for the three types of lighting systems (76%, 35%, and 58%, respectively). In industry, the end-use share assumptions are 10%, 20%, and 70% for the three lighting system types and the respective per-fixture savings assumptions are the same as those used for services. Many documented case studies of lighting retrofits now exist in the literature. For example, one recent installation of 1,000 dimming controls resulted in 25% savings at a cost of conserved energy of 2.3 cents/kWh (10).

<sup>c</sup> These savings primarily include those for more efficient motors, compressors, etc., as well as for adjustable-speed drives applied to systems that have energy losses due to part-load operation, and savings from improved system design, e.g., piping or ventilation duct sizing to minimize losses. Baseline service sector electricity use is given within the Vattenfall model. To define the relevant energy use in Swedish industry, we use the end-use data for motors, etc., in (11) and other sources. We have partitioned electricity used in industrial motors, pumps, etc., into two categories – one that is likely to be eligible for adjustable-speed drives and the other that has either implemented them already or has no opportunities. Efficiency options still exist within the second group (e.g., for system optimization and idling controls), but savings are less certain. We have treated mechanical pulping separately (about 5.6 TWh/year in 1987) and assume 10%, 20%, and 30% savings in the last three scenarios, based on (12) and (13). Savings from controls that reduce idling time may be as great as 40% in the Swedish paper and pulp industry, (personal communication, Bengt Lindahl, Scanpump, October 12, 1988). Measured savings of 22% from such controls have been documented for industrial applications in Japan (14). According to Baldwin's chapter, savings for ASDs alone can range from 25%-50% depending on the application (15).

<sup>d</sup> Detailed data for seven different technology improvements (retrofits and new appliances) in food preparation are given in (16); savings vary from 10-50%, depending on the measure and its application. Some of the savings would come from adjustable-speed drives, more-efficient compressors, refrigerator doors, and thicker insulation. Convective and microwave ovens contribute to savings in food preparation and ohmic heating reduces the electricity requirements for preserving certain food products (17). We assume that technology change is made at the time of equipment replacement as opposed to by retrofit.

<sup>e</sup> Office electronics electricity uses include computers, copiers, and printers. The savings estimates are based on the chapter by Norford *et al* in this volume (18). The continuing trend towards miniaturization and towards low-power transistors in computing equipment and input/output devices will lead to great efficiency gains. Other trends, such as the use of color monitors and laser printers are more electricity intensive than the processes they replace. Note Norford *et al*'s warning that nameplate ratings tend to overstate actual power requirements by a factor of 2-4 for personal computers and by a factor of 4-5 for printers. The authors also estimate that in the U.S. approximately 40% of office equipment is left running at night.

<sup>f</sup> The savings estimate in the efficiency scenarios is from the chapter by Abel in this volume. The stock average non-electric-heated commercial building today uses 100 kWh/m<sup>2</sup> annually. (For comparison, the California Title-24 standard for new buildings requires a maximum average electricity intensity (including air conditioning) of ~100 kWh/m<sup>2</sup> for new buildings for



large office buildings.) The difference between 140 kWh/m<sup>2</sup> and 50 kWh/m<sup>2</sup> corresponds to 1.2 TWh/year by the year 2010.

<sup>g</sup> In Sweden's industrial sector, by far the most important segment in terms of overall electricity demand is paper and pulp, which used 38% of the 46 TWh consumed by industry in 1987. Most of this was for motors and grinding equipment. Improvements to the grinding process are critical as are the opportunities for introducing new thermo- or chemo-mechanical pulping processes that are less electricity intensive. Improved water-removal techniques are also important.

<sup>h</sup> Examples of simple, fast-payback measures are given in (19). Reference Scenario estimates include the effect of the closure of some electric arc furnaces (EAFs) which affects the weighted averages given here. EAF savings for the other scenarios are counted separately in footnote "j" and do not assume any closures. In the Efficiency Scenario, before computing efficiency-related improvements, we incorporate 2.1 TWh<sub>e</sub> fuel switching to natural gas for process heating (and 2.8 TWh<sub>e</sub> in the last two Scenarios), based on (20) and on a review of this source by the Swedish Gas Association (Memorandum from Ulf Norhammar and Göran Engström, January 8, 1988. Stockholm). In the last two scenarios for EAFs, 0.6 TWh<sub>e</sub> is substituted for gas.

<sup>i</sup> We adopt the chemical industry estimate of savings potential (15%) (personal communication, Hans Wernborg, Swedish Chemical Industry Association (*Kemikontoret*), January 11, 1989). A recent case study shows even higher savings, based on actual savings from a retrofit at Gränges Aluminum in Sweden, which produces 24% of Sweden's aluminum. From an investment of \$43 million, product yield was increased from 13,500 tons/year to 22,500 tons/year and electricity intensity was reduced from 19 MWh/ton to 14 MWh/ton. The investment costs included non-energy improvements such as increased floor area and emissions controls. (Personal communication, Per-Olof Aronson, Gränges Aluminum. April 14, 1988.) The cost of conserved electricity for this case study is 2.6 cents/kWh. The overall potential savings for the sub-sector are uncertain because the remaining aluminum is produced in a plant today consuming approximately 17 MWh/ton, but the Gränges case is included in all but the Reference Scenario. The Reference Scenario includes some plant closures.

<sup>j</sup> In this volume, Eketorp describes many opportunities for improvements. In the Efficiency Scenario, savings result from electricity-efficiency measures (scrap pre-heating, improved transformers) and from increased quantities of oxygen and natural gas introduced into the furnace. The electricity requirement for manufacturing the oxygen (0.7–1.0 kWh/m<sup>3</sup>) is accounted for in the final savings estimate of 20% beyond today's furnaces, which averaged 590 kWh<sub>e</sub>/ton in 1987 in Sweden. In both the High-Efficiency and Advanced-Technology Scenarios, we assume the use of the Plasmascrap process for recycled scrap steel currently melted in electric-arc furnaces, EAFs. Plasmascrap requires one-quarter as much electricity as do Sweden's current EAFs. Pilot plants are in operation in Sweden, producing 1 ton molten steel per hour. Commercialization is possible within five years (personal communication, Sven Santen, Ovako Steel, February 2, 1989). Commercial units are expected to melt scrap steel with 150 kWh/ton.

<sup>k</sup> A large fuel-switching potential exists due to the flexibility of the Swedish stock of space-heating equipment. In single-family homes with multi-fuel heating systems, roughly 6 TWh of electricity are used for space heating. We assume that 90% of the homes respond in some way: of the respondents, four-fifths switch fuels and one-fifth (the highest-use households) install

earth-source heat pumps. We thus assume  $90\% \times 80\% = 72\%$  penetration of fuel switching. The heat pump COPs are 2.7 for the first efficiency scenario and 3.3 for the second and third, based on Bernström's chapter. In multi-family buildings, 2.6 TWh are consumed in multi-fuel systems. We assume 90% of these systems convert away from electricity. We also assume that 90% of the electricity used in multi-fuel systems in service sector buildings (0.9 TWh) is substituted for oil.

<sup>l</sup> Those homes that have no fuel flexibility consume about 13 TWh for electric space heating. One-third of these homes – by floor area – are served by hydronic systems, and consume 4.3 TWh. In our scenario, we convert 90% of these hydronic systems to earth-source heat pumps, with COPs same as in note "k". Great efficiency improvements have been made in recent years and are likely to continue. Only 3.5% of the existing single-family homes in Sweden today have electric heat pumps (21).

<sup>m</sup> Most large heat pumps for district heating are assumed to be replaced with fuel-based systems at the end of their useful lifetimes, except in the Advanced-Technology scenario where all are replaced.

<sup>n</sup> We consider wall and ceiling insulation for those homes heated with direct electric resistance systems. In 1987, the demand for space heating electricity in these homes (single-family only) was roughly 8.7 TWh. Based on the estimates of existing insulation levels of: ceiling 0.27 [W/m<sup>2</sup>-C] and walls 0.38 [W/m<sup>2</sup>-C], from the chapter by Elmroth, our scenarios upgrade U-values to 0.10 (ceilings) and 0.17 (walls) and assume 20% of the homes implement wall retrofits and 50% install roof insulation. Our assumption is based on limited technical opportunities (e.g., number of homes with room for insulation in attic spaces and the number of homeowners re-siding or re-roofing their houses before 2010). We estimate savings assuming a simple "U-value times surface area" calculation, based on Stockholm weather conditions. We adopt Elmroth's estimate that 0.7 TWh could be saved by adding a third pane to existing double-pane windows in homes with electric-resistance heating systems, and assume 45% of the homes find it possible to make the retrofit. Based on the large number of electric-resistance homes using over 30,000 kWh/year, we include the savings from earth-source heat pumps for those homes in this group that do not implement either wall or roof insulation. These homes and ~25,000 fuel-heated homes have separate electric water heaters, for which we assume 25% savings as the best-available models (more insulation in the tank wall) replace existing ones. We reduce these savings by two-thirds to compensate for increased space-heating needs and for limited penetration. In the Efficiency Scenario, 10% and 20% savings are assumed to result from insulating walls and roofs of multi-family buildings with direct electric heating systems or electric-only boilers (these homes consumed 1.4 TWh in 1987). For commercial buildings, we assume 20% and 15% savings, respectively, based on total use of 2.3 TWh in 1987. In direct-electric buildings, an additional 5% savings are assumed in the last two scenarios.

<sup>o</sup> This performance level is based on the chapter by Elmroth in this volume. For comparison, a home constructed to comply with the current Swedish Building Norm (SBN) standard would use about 5,000 kWh/y for space heating and 3,000 kWh/year for water heating. The primary physical differences between these two house types are in low-emissivity coatings or gas fill in the triple-glazed windows, reduced air infiltration, and higher quality control during construction.



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